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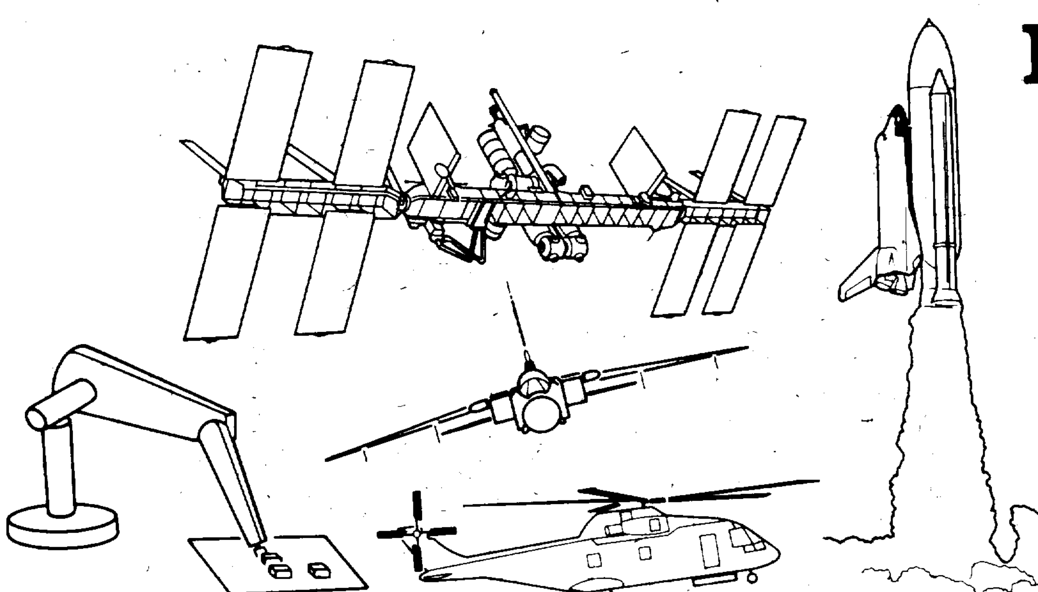
ABSTRACTS

3rd Annual Conference on Aerospace Computational Control

Radisson Suite Hotel
August 28-30, 1989
Oxnard, California



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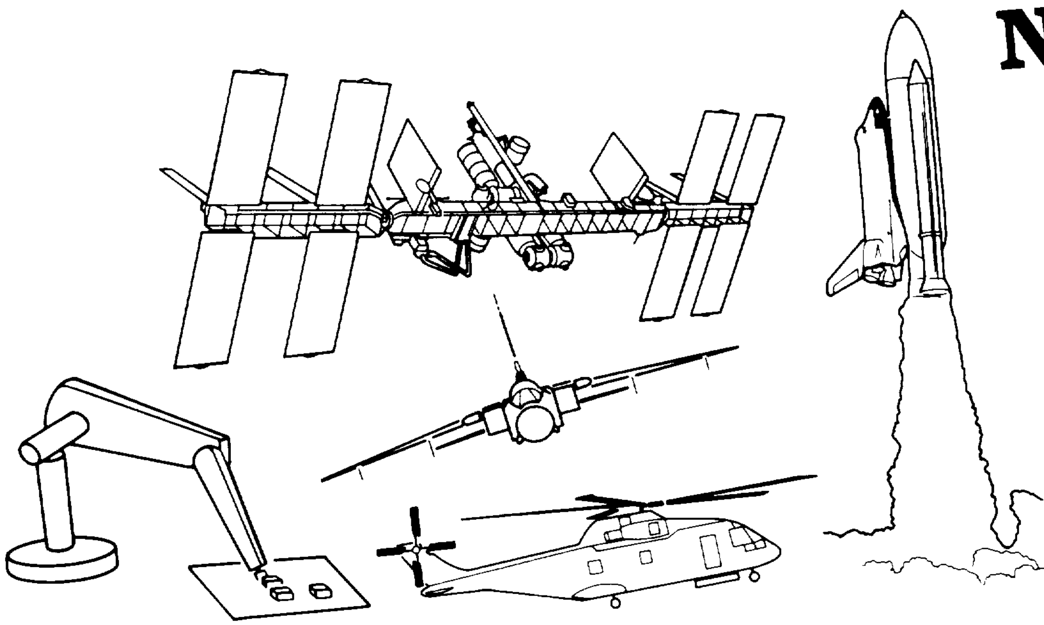

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MULTIBODY ADVANCED FORMULATION

A Spatial Operator Algebra For Rigid Multibody Modeling and Control

G. Rodriguez, K. Kreutz, and A. Jain
Jet Propulsion Laboratory/California Institute of Technology

Abstract

A recently developed spatial operator algebra, useful for modeling, control and trajectory design of open/closed chain rigid multibody systems is discussed. The elements of this algebra are linear operators whose domain and range spaces consist of forces, moments, velocities, and accelerations. The effect of these operators is equivalent to a spatial recursion along the span of the system. Inversion of operators can be efficiently obtained via techniques of recursive filtering and smoothing encountered in stochastic estimation and control theory. The operator algebra provides a high-level framework for describing the dynamic and kinematic behavior of the multibody system as well as control and trajectory design algorithms. The interpretation of expressions within the algebraic framework leads to enhanced conceptual and physical understanding of the system dynamics and kinematics. Furthermore, implementable O(N) recursive algorithms can be immediately derived from the abstract operator expressions by inspection. Thus, the transition from an abstract problem formulation and solution to the detailed mechanization of specific algorithms is greatly simplified.

An Order (n) Algorithm for the Dynamics Simulation of Robotic Systems

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NASA Goddard Space Flight Center

Abstract

The ability to simulate and analyze the dynamics of complicated multibody systems has been of great benefit to engineers for the past decade. Applications have included robotics, land vehicles, and spacecraft. However, many of the commercially available software have been computationally intensive and are costly and time-consuming for analyzing large systems. Fortunately, recent developments in Order (n) algorithms and parallel processing for multibody dynamics simulation have drastically reduced the computer time needed to simulate systems involving many bodies.

This paper presents the formulation of an Order (n) algorithm for DISCOS (Dynamics Interaction Simulation of Controls and Structures), which is an industry-standard software package for simulation and analysis of flexible multibody systems. For systems involving many bodies, the new Order (n) version of DISCOS is much faster than the current version. Results of the experimental validation of the dynamics software are also presented. The experiment is carried out on a seven-joint robot arm at NASA's Goddard Space Flight Center.

The algorithm used in the current version of DISCOS requires the inverse of a matrix whose dimension is equal to the number of constraints in the system. Generally, the number of constraints in a system is roughly proportional to the number of bodies in the system, and matrix inversion requires $O(p^3)$ operations, where p is the dimension of the matrix. The current version of DISCOS is therefore considered an Order (n^3) algorithm. In contrast, the Order (n) algorithm requires inversion of matrices which are small, and the number of matrices to be inverted increases only linearly with the number of bodies.

The newly-developed Order (n) DISCOS is currently capable of handling chain and tree topologies as well as multiple closed loops. Continuing development will extend the capability of the software to deal with typical robotics applications such as put-and-place, multi-arm hand-off and surface sliding.

Aspects of Efficient and Reliable Multibody System Simulation

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and
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Abstract

Multibody system equations can be generated in various forms. All of these may be interpreted as results of two basic approaches, the augmentation- and the elimination-method. The former method yields the descriptor form of the system motion, a set of differential-algebraic equations (DAE), and the latter the state space representation, a minimal set of ordinary differential equations (ODE). Both of these methods are surveyed. Particular emphasis is on the discussion of recursive computational schemes, generating the equations of motion with a number of operations, which is proportional to the number N of system bodies ($O(N)$-formulations).

For simulation purposes one would like to create that set of system equations, which can be generated most efficiently and for which the most efficient and reliable solution techniques are available. Numerical solution techniques for ODE have been studied in great detail and they are well-developed. By contrast, DAE have not been investigated for such a long time. In view of new developments in the latter field the generation of all the equations required for an efficient and reliable solution of DAE describing multibody system motion is discussed. These methods, i.e. an $O(N)$-formulation and new techniques for solving DAE, are implemented in the SIMPACK code. Its capabilities are illustrated by simulation of multibody robot models.

Contents

Systematic Generation of Multibody Equations of Motion Suitable for Recursive and Symbolic Manipulation

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A controversial issue in the past few years has been the choice and the number of coordinates in generating the multibody equations of motion. Some researchers have used a large number of absolute coordinates which yields a large set of loosely coupled differential-algebraic equations, while others have used a minimum or a small number of generalized coordinates that yields a small set of highly coupled differential or differential-algebraic equations. This paper presents a systematic method for deriving the minimum number of equations of motion for multibody systems containing open- and closed-kinematic loops. The resulting set of equations has the advantage of both absolute and generalized coordinate formulations. In this formulation, a set of joint coordinates is used to describe the configuration of the system. The constraint equations associated with the closed-kinematic loops are found systematically in terms of the joint coordinates. These contraints and their corresponding elements are constructed from known block matrices representing different kinematic joints. The Jacobian matrix associated with these constraints is further used to find a velocity transformation matrix. The equations of motions are initially written in terms of the dependent joint coordinates using the Lagrange multiplier technique. Then a velocity transformation matrix is used to derive the minimum number of equations of motion in terms of a set of independent joint coordinates.

This formulation has the following features: (a) The equations of motion can be developed in a form that is computationally most suitable for a particular system; (b) the equations of motion can be solved either recursively or nonrecursively depending upon the topology of the system in order to gain maximum computational efficiency; (c) the formulation is suitable for symbolic code generation; (d) the multibody system can contain both rigid and deformable bodies. The derivation of the equations of motion for rigid and flexible bodies will be shown in the paper, and the computational aspects will be discussed. Illustrative examples and numerical results will be presented.

Recursive Linearization of the Multibody Dynamics Equations of Motion

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The University of Iowa

The equations of motion of a multibody system are non-linear in nature, thus pose a difficult problem in linear control design. One approach is to have a first-order approximation through the numerical perturbations at a given configuration, and to design control based on that linearized model. In this paper, a linearized model is generated analytically following the footsteps of the recursive derivation of the equations of motion.

The equations of motion are first written in a Newton-Euler form, which is systematic and easy to construct; then, they are transformed into a relative coordinate representation, which is more efficient in computation. A new computational method for linearization is obtained by applying a series of first-order analytical approximations to the recursive kinematic relationships. The method proved to be computationally more efficient because of the recursive nature. It also turned out to be more accurate because of the fact that analytical perturbation circumvents numerical differentiation and other associated numerical operations that may accumulate computational error, thus requiring only analytical operations of matrices and vectors.

The power of the proposed linearization algorithm is demonstrated, in comparison to a numerical perturbation method, with a double pendulum and a seven degree-of-freedom robotic manipulator. Its application to control synthesis is also demonstrated.

An Innovations Approach to Decoupling of Multibody Dynamics and Control

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Abstract

The paper solves the problem of hinged multibody dynamics using an extension of the innovations approach of linear filtering and prediction theory to the problem of mechanical system modeling and control. This approach has been used quite effectively to diagonalize the equations for filtering and prediction for linear state space systems. It has similar advantages in the study of dynamics and control of multibody systems. The innovations approach advanced here consists of expressing the equations of motion in terms of two closely related processes: (1) the innovations process ε, a sequence of moments, obtained from the applied moments T by means of a spatially recursive Kalman filter that goes from the tip of the manipulator to its base; (2) a residual process, a sequence of velocities, obtained from the joint-angle velocities by means of an outward smoothing operations. The innovations ε and the applied moments T are related by means of the relationships $\varepsilon = (I - L)T$ and $T = (I + K)\varepsilon$. The operation $(I - L)$ is a causal lower triangular matrix which is generated by a spatially recursive Kalman filter and the corresponding discrete-step Riccati equation. Hence, the innovations and the applied moments can be obtained from each other by means of a causal operation which is itself causally invertible. The residuals ν and the joint-angle velocities $\dot{\theta}$ are related by $\nu = (I - K^*)\dot{\theta}$ and $\dot{\theta} = (I - L^*)\nu$ in which $(I - L^*)$ is also an anticausal, upper-triangular, matrix. Hence, the residuals and the joint-angle velocities are related by means of an anticausal operation which is itself anticausally invertible. The use of the residuals process is of interest because it diagonalizes the composite multibody system kinetic energy. In other words, the kinetic energy $J(\dot{\theta}, \theta)$ in the system can be written as $J = 1/2\nu^T D\nu$ in which D is a diagonal matrix. The Lagrangian equations of motion that result from this diagonal form for the kinetic energy are completely decoupled in the sense that the equation for the residual

velocity at any given joint is independent from the similar equations at all of the remaining joints. The innovations process appears as a driving term in these equations. Use of the innovations, in place of the physically applied joint moments, decouples the equations even further. The equations of motion for joint k involves only the value of the innovations at the same joint. The final equations of motion are therefore diagonalized in the sense that the equation for any given joint is independent from the equations at the other joints. The diagonal form of the equations of motion results in significant simplification of dynamic analysis, simulation, stability analysis, and control design. This simplicity is illustrated by arriving a very simple decoupled control algorithms for robotic manipulator control.

Efficient Dynamic Simulation For Multiple-Chain Robotic Mechanisms

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Abstract

Recently, there has been an increasing interest in robotic systems with multiple chains forming simple closed-kinetic loops. Such systems of interest in space robotics applications include multilegged vehicles, multiple manipulators, and dextrous hands. Each is characterized by multiple chains of links (legs, arms, or fingers) in support of a body, load, or object. Real-time simulation of these systems is important for remote operation, but difficult to achieve at present. An even greater challenge to the computational engineer is that of *super-real-time simulation* (planning seconds of motion in milliseconds). This has been shown to be of value in the control of a multilegged vehicle when predicting the action of the present control to ensure safety and stability along a planned trajectory. In this paper, an $O(N)$ algorithm for dynamic simulation will be presented, where N is the number of degrees of freedom for each chain. It is based on computation of the operational space inertia matrix (6x6) for each chain as seen by the body, load, or object. Determination of the articulated body inertia[†] is a key part of the computation. Also, computation of the chain dynamics, when opened at one end, is required, and the most efficient algorithm is used for this purpose. Parallel implementation of the dynamics for each chain results in the $O(N)$ algorithm. Further details of the algorithm will be given in the paper, along with illustration through and example system.

†R. Featherstone, "The Calculation of Robot Dynamics Using Articulated-Body Inertias," *The International Journal of Robotics Research*, Vol. 2, No. 1, pp. 13-30, Spring 1983.

A Nearly-Linear Computational-Cost Scheme for the Forward Dynamics of an N-Body Pendulum

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Abstract

The dynamic equations of motion of an n-body pendulum with spherical joints are derived to be a mixed system of differential and algebraic equations (DAEs). The DAEs are kept in implicit form to save arithmetic and preserve the sparsity of the system and are solved by the robust implicit integration method. At each solution point, the predicted solution is corrected to its exact solution within given tolerance using Newton's interative method. For each iteration, a linear system of the form $\mathbf{Ax} = \mathbf{b}$ has to be solved. The computational cost for solving this linear system directly by LU factorization is $O(n^3)$, and it can be reduced significantly by exploring the structure of $\mathbf{A}$. This paper shows that by recognizing the recursive patterns and exploiting the sparsity of the system the multiplicative and additive computational costs for solving $\mathbf{Ax} = \mathbf{b}$ are $O(n)$ and $O(n^2)$, respectively. The modeling, formulation, and solution method for an n-body pendulum is presented. The computational cost is shown to be nearly linearly proportional to the number of bodies.

CONTROL DESIGN
AND ANALYSIS I

Sliding Control of Pointing and Tracking with Operator Spline Estimation*

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3rd Annual Conference on Aerospace Computation Control

Abstract

It is shown in this paper how a variable structure control technique could be implemented to achieve precise pointing and good tracking of a deformable structure subject to fast slewing maneuvers. The correction torque that has to be applied to the structure is based on estimates of upper bounds on the model errors. For a rapid rotation of the deformable structure, the clastic response can be modeled by oscillators driven by angular acceleration, and where stiffness and damping coefficients are also angular velocity and acceleration dependent. By transforming this "slew-driven" elastic dynamics into bilinear form (by regarding the vector made up of the angular velocity, squared angular velocity and angular acceleration components, which appear in the coefficients as the input to the deformation dynamics), an operator spline can be constructed, that gives a low order estimate of the induced disturbance. Moreover, a "worst case" error bound between the estimated deformation and the unknown exact deformation is also generated, which can be used where required in the sliding control correction.

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A Survey on the Structured Singular Value

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Abstract

The structured singular value, μ, is an important linear algebra tool to study a class of matrix perturbation problems. It is useful for analyzing the robustness of stability and performance of uncertain, (nominally) linear systems. Computation of $\mu(M)$ is difficult, and usually, upper and lower bounds are all that can be reliably computed. Upper bounds give conservative estimates of the sizes of allowable perturbations. The maximum singular value of a matrix M is an upper bound for $\mu(M)$. As an upper bound, it can be improved by finding a transformations to the data (ie. M) which do not change the structured singular value, but do reduce the maximum singular value. Typically, upper bound algorithms involve searches over sets of transformations to yield the tightest bound. Lower bound algorithms produce small, destabilizing perturbations. In general, the algorithms are intelligent searches for minimum-norm solutions to multivariable polynomial equations, and are based on various optimality conditions that hold at the global (and, unfortunately, some local) minima. This paper reviews the current methods to compute both of these types of bounds, covering theoretical justification and extensive numerical experience with the various algorithms.

Algorithms for Computing Multivariable Structured Stability Margin

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Abstract

Algorithms based on nondifferentiable optimization theory for computing the Structured Stability Margin (SSM) are presented. The SSM of a matrix G, denoted km(G), is the "size" of the smallest diagonal matrix $\Delta = \text{diag}(\Delta 1, \ldots, \Delta n)$ for which $\det(I + \Delta G) = 0$. Two cases are treated, the one-sided case in which $\Delta \in [0, \infty)$ and the two-sided case in which $\Delta \in (-\infty, \infty)$. These algorithms have been coded and appear to be highly reliable. Flight control examples are presented in which Bode plots of $k_m(G(jw))$ are used to evaluate robustness and performance.

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Robustness Analysis for Real Parametric Uncertainty*

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Abstract

This paper has a twofold purpose. First, to review some key results in the literature in the area of robustness analysis for linear feedback systems with structured model uncertainty, and secondly to present some new results.

Model uncertainty is described as a combination of real uncertain parameters and norm bounded unmodeled dynamics. We will mainly focus on the case of parametric uncertainty. An elementary and unified derivation of the celebrated theorem of Kharitonov and the Edge Theorem will be presented. Next, an algorithmic approach for robustness analysis in the cases of multilinear and polynomic parametric uncertainty (i.e. the closed loop characteristic polynomial depends multilinearly and polynomially respectively on the parameters) is given. The latter cases are most important from practical considerations.

Some novel modifications in this algorithm which result in a procedure of polynomial time behavior in the number of uncertain parameters will be outlined. Finally, we show how the more general problem of robustness analysis for combined parametric and dynamic (i.e. unmodeled dynamics) uncertainty can be reduced to the case of polynomic parametric uncertainty, and thus be solved by means of our algorithm.

*To be presented at the 3rd Annual Conference on Aerospace Computational Control, Oxnard CA, August 1989.

Computational Issues in the Analysis of Adaptive Control Systems

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Abstract

Adaptive systems under slow parameter adaptation can be analyzed by the method of averaging. This provides a means to assess stability (and instability) properties of most adaptive systems, either continuous-time or (more importantly for practice) discrete-time, as well as providing an estimate of the region of attraction. Although the method of averaging is conceptually straightforward, even simple examples are well beyond hand calculations. Specific software tools are proposed which can provide the basis for user-friendly environment to perform the necessary computations involved in the averaging analysis.

Experimental Experience with Flexible Structures

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Abstract

This paper will focus on a flexible structure experiment developed at the California Institute of Technology. The main thrust of the experiment is to address the identification and robust control issues associated with large space structures by capturing their characteristics in the laboratory. The design, modeling, identification and control objectives will be discussed within this paper. Also, the subject of uncertainty in structural plant models and the frequency shaping of performance objectives will be expounded upon. Theoretical and experimental results of control laws designed using the identified model and uncertainty descriptions will be presented.

A Disturbance Based Control/Structure Design Algorithm

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Abstract

An algorithm for the integrated optimal control/structure design problem is developed by considering the structure's dynamic response to a stochastic disturbance model. The design objective is to minimize the structural weight subject to a set of static structural constraints and dynamic response constraints. The control/structure interaction is provided by constraints on the allowable dynamic output response and on allowable control energy. Controller design can be quite general, and examples to date have applied full state (LQR), observer output, and positive real feedback control strategies. Numerical solutions are obtained by either the iterative construction and solution of a sequence of explicit approximate problems using a general nonlinear programming package, or through sequential linear programming and a continuation technique. Examples are presented illustrating the design algorithm applied to repre-sentive structures with differing design requirements and controller methodologies.

The Use of Deflation in Eigenassignment Problems

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Abstract

Deflation is a technique used by algorithms that solve the eigenproblem of a matrix A. According to this technique once an eigenpair (λ_1, x_1) of A is computed, the algorithm continues with a matrix which possesses only the remaining eigenvalues. Deflation can be accomplished by using a variety of methods. One particular method, based on orthogonal (or unitary) similarity transformations, has nice numerical properties, consequently it has been very popular amongst numerical analysts. This method has successfully been used on other problems as well. Amongst these problems is the **Eigenvalue Assignment Problem Using State Feedback**, where given $A \varepsilon \mathbb{R}^{nxn}$, $B \varepsilon \mathbb{R}^{nxm}$ and a self conjugate set of eigenvalues λ_i, $i = 1,2,\cdots,n$ we need to compute $F \varepsilon \mathbb{R}^{mxn}$ such that the eigenvalues of $A - BF$ are λ_i, $i = 1,2,\cdots,n$. We show that two well known algorithms for the above problem both use deflation based on orthogonal similarity transformations as follows:

1. An eigenvector x_1 of A – BF corresponding to, say λ_1 is computed, with $||x_1||_2=1$.
2. The first column of F is computed so that $A - BF$ possesses the eigenpair (λ_1, x_1).
3. A unitary matrix $Q = (x_1, \tilde{Q})$ is computed.
4. The similarity transformations $Q^H(A - BF)Q = \begin{pmatrix} \lambda_1 & x_1^H(A-BF)\tilde{Q} \\ \hline & Q_H(A-BF)\tilde{Q} \end{pmatrix}$ is performed.
5. The assignment is continued with $\tilde{Q}^H(A - BF)\tilde{Q}$.

Based on the above, we point out that the problem becomes trivial when a desired set of feasible eigenvectors is also given. We also suggest how deflation based on orthogonal (or unitary) similarity transformations may be used for the solution of the **Eigenvalue Assignment Problem Using Output Feedback**.

Combined Control-Structure Optimization

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Abstract

This paper outlines the development of methods for the combined control-structure optimization of physical systems encountered in the technology of large space structures. The main drivers for our work include applications to large interferometer missions that require microprecision pointing and optical path length stability.

The optimal design of a structural system whose response to disturbances must be controlled to meet certain performance criteria has traditionally proceeded along two separate but sequential paths. First, the structure is optimized by selecting structural design variables which minimize a structural criterion. Then with the structural design thus determined, a control objective is optimized by selecting an optimal set of control design variables which minimize a control design criterion. In the combined control-structure optimization, one starts by formulating a single objective criterion that consists of a combination of the structural criteria and the control criteria.

The ultimate utility of a combined control structure optimization formulation is not strictly determined by the relevancy of a single cost criterion, but rather lies in the ability to quickly, reliably, and methodically search the design space and to effect rational trades between design variables. With this objective in mind, this paper considers model problem formulations for combined control-structure optimization and develops corresponding approximation methods which exploit techniques of homotopy continuation and parametric regularization.

PARALLEL PROCESSING I

Parallel Processing of Realtime Dynamic Systems Simulation on Oscar (Optimally Scheduled Advanced Multiprocessor

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Abstract

This paper presents parallel processing of realtime dynamic systems simulation on a multiprocessor system named OSCAR. In the simulation of dynamic system, generally, the same calculation including numerical integration methods are repeated every time step. However, we cannot apply the Do-all or Do-across techniques for parallel processing of the simulation since there exists data dependencies from the end of previous iteration to the beginning of the following iteration and furthermore data input and output are required every sampling time period. Therefore, parallelism inside the calculation of a single time step, or a loop body, must be used. In the proposed method, near fine grain tasks, each of which consists of one or more floating operations, are generated to extract the parallelism from the calculation and assigned to processors by using optimal static scheduling at compile time in order to reduce large run time overhead caused by the use of near fine grain tasks. The practicality of the schemem is demonstrated on OSCAR (Optimally Scheduled Advanced multiprocessor) which has been developed to extract advantageous features of static scheduling algorithms to the maximum extent.

Parallel and Vector Computation for Stochastic Optimal Control Applications

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Abstract

A method for parallel and vector numerical solutions of stochastic dynamic programming problems is described for optimal control of general nonlinear, continuous time dynamical systems, perturbed by Poisson as well as Gaussian random white noise. Possible applications include lumped flight dynamics models for uncertain environments, such as large scale and background random atmospheric fluctuations. The numerical formulation is highly suitable for a vector multiprocessor or vectorizing supercomputer, and results exhibit high processor efficiency and numerical stability. Advanced computing techniques, data structures, and hardware help alleviate Bellman's *curse of dimensionality* in dynamic programming computations.

A Robot Arm Simulation with a Shared Memory Multiprocessor Machine

Sung-Soo Kim and Li-Ping Chuang
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The University of Iowa

Abstract

A parallel processing scheme for a single chain robot arm is presented for high speed computation on a shared memory multiprocessor. A recursive formulation that is derived from a virtual work form of the d'Alembert equations of motion is utilized for robot arm dynamics. A joint drive system that consists of a motor rotor and gears is included in the arm dynamics model, in order to take into account gyroscopic effects due to the spinning of the rotor. The fine grain parallelism of mechanical and control subsystem models is exploited, based on independent computation associated with bodies, joint drive systems, and controllers. Efficiency and effectiveness of the parallel scheme are demonstrated through simulations of a telerobotic manipulator arm. Two different mechanical subsystem models, i.e., with and without gyroscopic effects, are compared, to show the trade-off between efficiency and accuracy.

A Unifying Framework for Rigid Multibody Dynamics and Serial and Parallel Computational Issues

Amir Fijany and Abhinandan Jain
Jet Propulsion Laboratory/California Institute of Technology

Abstract

In this paper we present a unifying framework for various formulations of the dynamics of open-chain rigid multibody systems and assess their suitability for serial and parallel processing. The framework is based on the derivation of intrinsic, i.e., coordinate–free, equations of the algorithms which provides a suitable abstraction and permits a distinction to be made between the computational redundancy in the intrinsic and extrinsic equations. A set of spatial notation is used which allows the derivation of the various algorithms in a common setting and thus clarifies the relationships among them. The three classes of algorithms viz., $O(n)$, $O(n^2)$ and $O(n^3)$ or the solution of the dynamics problem are investigated. We begin with the derivation of $O(n^3)$ algorithms based on the explicit computation of the mass matrix and it provides insight into the underlying basis of the $O(n)$ algorithms. From a computational perspective, the optimal choice of a coordinate frame for the projection of the intrinsic equations is discussed and the serial computational complexity of the different algorithms is evaluated. The three classes of algorithms are also analyzed for suitability for parallel processing. It is shown that the problem belongs to the class of NC and the time and processor bounds are of $O(\log_2^2(n))$ and $O(n^4)$, respectively. However, the algorithm that achieves the above bounds is not stable. We show that the fastest stable parallel algorithm achieves a computational complexity of $O(n)$ with $O(n^4)$, respectively. However, the algorithm that achieves the above bounds is not stable. We show that the fastest stable parallel algorithm achieves a computational complexity of $O(n)$ with $O(n^2)$ processors, and results from the parallelization of the $O(n^3)$ serial algorithm.

Parallel Algorithms and Architecture for Computation of Manipulator Forward Dynamics

Amir Fijany
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Abstract

In this paper parallel algorithms for computation of multibody dynamics as specialized to the case of robot manipulator are presented. Considering three class of serial algorithms for the solution of the problem, i.e., the $O(n)$, the $O(n^2)$, and the $O(n^3)$ algorithms, time and processors bounds in the parallel computation are investigated. It is shown that the problem belongs to the class of *NC* and that the time and processors bounds are of $O(\log_2^2 n)$ and $O(n^4)$ respectively. However, the fastest stable parallel algorithms achieve the computation time of O(n) and can be derived by parallelization of the $O(n^3)$ serial algorithms.

Parallel computation of the $O(n^3)$ algorithms requires the development of parallel algorithms for a set of fundamentally different problems, that is; the Newton-Euler formulation, the computation of the inertia matrix and its decomposition, and the solution of triangular systems. Parallel algorithms for this set of problems are developed which can be efficiently implemented on a unique architecture, i.e., a triangular array of n(n+1)/2 processors with a simple nearest-neighbor interconnection. This architecture is particularly suitable for VLSI and WSI implementations. Particular attention is paid to the communication cost and overhead due to the dynamic organization of the data. It is shown that, even with a simple nearest-neighbor interconnection, a communication complexity of $O(n)$ can be achieved. The mechanisms for satisfying the global and local synchronization requirements of the algorithms are also analyzed.

The developed parallel algorithm, compared to the best serial $O(n)$ algorithm, provide about two-order of magnitude asymptotic speed-up in the computation. The results of this paper clearly prove the validity of the massively parallel processing approach to the multibody dynamics computation.

Computational Dynamics for Robotics Systems Using a Non-Strict Computational Approach

David E. Orin,† P. Sadayappan,‡ and Ho-Cheung Wong†
Ohio State University

Abstract

This paper proposes a Non-Strict approach to computing the dynamics for real-time robotics systems. In contrast to the traditional approach to scheduling such computations, based strictly on task dependence relations, the proposed approach relaxes precedence constraints and scheduling is guided instead by the relative sensitivity of the outputs with respect to the various paths in the task graph. An example of the computation of the Inverse Dynamics of a simple inverted pendulum is used to demonstrate the reduction in effective computational latency through use of the Non-Strict approach. A speedup of 5 has been obtained when the processes of the task graph are scheduled to reduce the latency along the crucial path of the computation. While error is introduced by the relaxation of precedence constraints, the Non-Strict approach has a smaller error than the conventional Strict approach for a wide range of input conditions.

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"Computational Chaos" in Massively Parallel Neural Networks

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Abstract

A fundamental issue which directly impacts the scalability of current theoretical neural network models to massively parallel embodiments, in both software as well as hardware, is the inherent and unavoidable concurrent asynchronicity of emerging fine-grained computational ensembles and the possible emergence of chaotic manifestations. Previous analyses attributed dynamical instability to the topology of the interconnection matrix, to parasitic components or to propagation delays. However, we have observed the existence of "emergent" computational chaos in a "concurrently asynchronous" framework, independent of the network topology. In this paper we present a methodology enabling the effective asynchronous operation of large-scale neural networks. Necessary and sufficient conditions guaranteeing concurrent asynchronous convergence are established in terms of contracting operators. Lyapunov exponents are computed formally characterize the underlying nonlinear dynamics. Simulation results are presented to illustrate network convergence to the correct results, even in the presence of "large" delays.

This research was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract NAS-918 with NASA. Support for the work came from agencies of the U.S. Department of Defense, including the Innovative Science and Technology Office of the Strategic Defense Initiative Organization.

MULTIBODY ADVANCED
FORMULATION II

Multi-Flexible-Body Dynamics Capturing Motion-Induced Stiffness

Arun K. Banerjee*, Mark E. Lemak**, and John M. Dickens***
Lockheed Missiles & Space Co.

Abstract

This paper presents a multi-flexible-body dynamics formulation incorporating a recently developed theory for capturing motion induced stiffness for an arbitrary structure undergoing large rotation and translation accompanied by small vibrations. In essence, the method consists of correcting prematurely linearized dynamical equations for an arbitrary flexible body with generalized active forces due to geometric stiffness corresponding to a system of twelve inertia forces and nine inertia couples distributed over the body. Equations of motion are derived by means of Kane's method. A useful feature of the formulation is its treatment of prescribed motions and interaction forces. Results of simulations of motions of three flexible spacecraft, involving stiffening during spinup motion, dynamic buckling, and a repositioning maneuver, demonstrate the validity and generality of the theory.

* Senior Staff Engineer
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Nonlinear Strain-Displacement Relations in the Dynamics of a Two-Link Flexible Manipulator

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MIT

Abstract

The equations of motion of a flexible, two-link, planar manipulator are derived via the Kane formalism, correctly linearized in small elastic deflections and speeds through the use of nonlinear strain-displacement relations. Ordinary differential equations are obtained as a result of modelling the links as Bernoulli-Euler beams and expanding the elastic deflections in terms of cantilever modes. A simulation is implemented that allows the determination of the manipulator's dynamic response to desired forcing functions in the form of joint torques. Slew maneuver simulation results are then compared for models with and without the properly modeled kinematics of deformation, in order to quantify the relative significance of certain nonlinear terms in the motion equations. It is found that rigid body motion limits exist below which elastic nonlinear terms are negligible. These are nonlinear terms that involve the generalized elastic coordinates and their time derivatives. These rigid body motion limits are set by the requirement that inconsistently linearized equations of motion (those derived using linear strain-displacement or linear kinematics of deformation) yield accurate results. Within these limits, it is found that equations derived ignoring all elastic nonlinear terms produce simulation results that are as good as the inconsistently and consistently linearized equations.

Nonlinear Finite Element Formulation for the Large Displacement Analysis in Multibody System Dynamics

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Abstract

A total Lagrangian finite element formulation for the deformable bodies in multibody mechanical systems that undergo finite relative rotations is developed. The deformable bodies are discretized using finite element methods. The shape functions that are used to describe the displacement field are required to include the rigid body modes that describe only large translational displacements. This does not impose any limitations on the technique because most commonly used shape functions satisfy this requirement. The configuration of an element is defined using four sets of coordinate systems: Body, Element, Intermediate element, Global. The body coordinate system serves as a unique standard for the assembly of the elements forming the deformable body. The element coordinate system is rigidly attached to the element and therefore it translates and rotates with the element. The intermediate element coordinate system, whose axes are initially parallel to the element axes, has an origin which is rigidly attached to the origin of the body coordinate system and is used to conveniently describe the configuration of the element in undeformed state with respect to the body coordinate system. A mixed sets of Cartesian translational and rotational coordinates are used in order to define the location and orientation of the deformable body coordinate system with respect to global inertial frame of reference. The nonlinear dynamic equations of motion developed, for deformable multibody systems that undergo large relative displacements, are expressed in terms of a unique set of time-used. These invariants can be generated for each finite element prior to dynamic analysis. The invariants of the deformable body can be obtained by assembling the invariants of the elements using a standard

processor. The nonlinear formulation presented in this paper has been implemented in the general purpose computer program DAMS (Dynamic Analysis of Multibody Systems) that automatically constructs and numerically solves the nonlinear equations of motion of multibody systems consisting of interconnected rigid and deformable bodies. The linearization used in other finite element methods (such as the updated Lagrangian formulation) for describing the large displacements of deformable bodies is also discussed.

Optimum Control Forces for Multibody Systems with Intermittent Motion

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Abstract

It is common practice in the analysis of constrained multibody systems to apply the constraints as a set of separate algebraic equations and embed them into the governing equations for the specified time of the simulation. However more realistic systems are those where different constraints could be applied at different times, and hence the multibody system must be able to accommodate for the sudden changes. If the multibody system doesn't develop the appropriate initial conditions to satisfy the constraints whenever they are applied, the system performance will then be hampered and it will fail to accomplish its tasks.

If a multibody system is subjected to constraint equations that are released and applied at different times during the motion they characterize the so-called intermittent constraints. This paper objective is to address the continuity of motion when a dynamical system is suddenly subjected to constraint conditions. Motion discontinuity due to the initial constraint violation is avoided by prior control forces that adjust the motion and yield velocity and acceleration consistent at the point of application of the constraint. The optimum control forces are determined for a specified control interval. The method proposed provides an optimum adjustment of the system's motion and assures that the stresses developed at the system components are kept within acceptable limits. The procedures developed will be illustrated making use of inequality constraints applied to obstacle avoidance problems in robotics.

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Development of Efficient Computer Program for Dynamic Simulation of Telerobotic Manipulation

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Abstract

Research in robot control has generated interests in computationally efficient forms of dynamic equations for multi-body systems. For a simply connected open-loop linkage, dynamic equations arranged in recursive form has been found to be particularly efficient. A general computer program capable of simulating open-loop manipulator with arbitrary number of links has been developed based on an efficient recursive form of Kane's dynamic equations. Also included in the program is some of the important dynamics of the joint drive system, i.e., the rotational effect of the motor rotors. Further efficiency is achieved by the use of symbolic manipulation program to generate the FORTRAN simulation program tailored for a specific manipulator based on the parameter values given. This paper describes the formulations and the validation of the program, and it also shows some sample runs.

The Coupling Effects of Kinematics and Flexibility on the Lagrangian Dynamic Formulation of Open Chain Deformable Links

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Abstract

In this paper a nonlinear Lagrangian formulation for the spatial kinematic and dynamic analysis of open chain deformable links consisting of cylindrical joints that connects pair of flexible links is developed. The special cases of revolute or prismatic joint can also be obtained form the kinematic equations. The kinematic equations are described using 4x4 matrix method. The configuration of each deformable link in the open loop kinematic chain is identified using a coupled set of relative joint variables, costant geometric parameters, and elastic coordinates. The elastic coordinates define the link deformation with respect to a selected joint coordinate system that is consistent with the kinematic constraints on the boundary of the deformable link. These coordinates can be introduced using approximation techniques such as Rayleigh-Ritz method, finite element technique or any other desired approach. The large relative motion between neighboring links are defined by a set of joint coordinates which describes the large relative translational and rotational motion between two neighboring joint coordinate systems. The origin of these coordinate systems are rigidly attached to the neighboring links at the joint definition points along the axis of motion. The geometry of the deformable links are included in the formulation by two costant parameters which accounts for the length and twist of the deformable link in tis undeformed state. The kinematic equations that define the global position and velocity of an arbitrary point on a deformable link is developed in terms of the relative joint variable, constant geometric parameters, and elastic coordinates of deformable links. These kinematic equations are then used to develop the energy expression of the deformable link. The nonlinear terms that represent the dynamic coupling between the large relative motion and the mall elastic deformations is identified and presented in terms of a set of time-invariant quantities that depend on the assumed displacement field

and provide a systematic approach to study the spatial dynamics of open loop kinematic chains. The system differential equations are then developed and expressed in terms of these set of invariant quantities using Lagrange's equation of motion.

Explicit Modeling of Composite Plates and Beams in the Dynamics of Multibody Systems

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Abstract

The state of the art dynamic response analysis of flexible multibody systems is currently restricted to elastic bodies with homogeneous materials. The requirements for high speed operation has made it necessary to use lightweight multi layered composite bodies in robotic systems and space structure applications. Dynamic modeling and analysis of such systems are particularly important since the effects of body flexibility to the performance are likely to be more pronounced.

In this paper first the eight-noded isoperimetric quadrilateral element with independent rotational and displacement degrees of freedom is extended to laminated composite elements. The element includes an arbitrary number of bonded layers, each of which may have a different thickness. The transverse shear deformation which is a predominant factor in the analysis of laminated composite structures is taken into account in developing the stiffness and mass matrices. The corresponding 3-D mode shapes are then incorporated to the multibody system dynamical equations. Floating body reference frames allow the selection of different boundary conditions, and the dynamical equations contain all the nonlinear interactions between the rigid and elastic motion. Example simulations are presented to illustrate the methods proposed.

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Experimental Verification of Dynamics Simulation

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Abstract

The dynamics model here is a backhoe, which is a four degree of freedom manipulator from the dynamics standpoint. Two types of experiments are chosen that can also be simulated by a multibody dynamics simulation program. In the experiment, recorded were the configuration and force histories; that is, velocity and position, and force output and differential pressure change from the hydraulic cylinder, in the time domain.

When the experimental force history is used as driving force in the simulation model, the forward dynamics simulation produces a corresponding configuration history. Then, the experimental configuration history is used in the inverse dynamics analysis to generate a corresponding force history. Therefore, two sets of configuration and force histories--one set from experiment, and the other from the simulation that is driven forward and backward with the experimental data--are compared in the time domain. More comparisons are made in regard to the effects of initial conditions, friction and viscous damping.

CONTROL DESIGN
AND ANALYSIS II

Frequency Response Modeling and Control of Flexible Structures: Computational Methods[1]

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Abstract

The dynamics of vibrations in flexible structures can be conveniently modeled in terms of frequency response to various localized or spatial excitation. For structural control such models capture the *distributed parameter* dynamics of the elastic structural response as an irrational transfer function from localized actuation to localized deformation measurements. For most flexible structures arising in aerospace applications the irrational transfer functions which arise are of a special class of pseudo-meromorphic functions which have only a finite number of right half plane poles. In this talk, we demonstrate computational algorithms for design of multiloop control laws for such structures based on optimal Wiener-Hopf control of the frequency responses. The algorithms employ a sampled-data representation of irrational transfer functions which is novel and particularly attractive for numerical computation. One key algorithm for the solution of the optimal control problem is the spectral factorization of an irrational transfer function. The algorithm described is an extension of a Newton-Raphson iteration for the matrix spectral factorization first demonstrated by J. Davis. We describe the implementation of the spectral factorization algorithm together with other computational components for control design of flexible structures. We also highlight options for implementation of wide band vibration control for flexible structures based on the sampled-data frequency response models. Examples of frequency response models and control laws for flexible structures will be discussed.

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[1] Work supported by SDIO and Air Force WRDC under contract F33615-88-C-3215.

Efficient Computer Algebra Algorithms for Polynomial Matrices in Control Design

J. S. Baras
D. C. MacEnany
R. Munach

Abstract

The theory of polynomial matrices plays a key role in the design and analysis of multi-input multi-output control and communications systems using frequency domain methods. Examples include coprime factorizations of transfer functions, canonical realizations from matrix fraction descriptions, and the transfer function design of feedback compensators. Typically, such problems abstract in a natural way to the need to solve systems of Diophantine equations (the so-called generalized Bezout equations) or systems of linear equations over polynomials. These and other problems involving polynomial matrices can in turn be reduced to polynomial matrix triangularization procedures, a result which is not surprising given the importance of matrix triangularization techniques in numerical linear algebra. There, we deal with matrices with entries from a field and Gaussian elimination plays a fundamental role in understanding the triangularization process. In the case of polynomial matrices we are dealing with matrices with entries from a ring for which Gaussian elimination is not defined and triangularization is accomplished by what is quite properly called Euclidean elimination.

Unfortunately, the nmerical stability and sensitivity issues which accompany floating point approaches to Euclidean elimination are not very well understood at present. In this paper we present new algorithms which circumvent entirely such numerical issues through the use of exact, symbolic methods in computer algebra. The use of such error-free algorithms guarantees that the results are accurate to within the precision of the model data—the best that can be hoped. Care must be taken in the design of such algorithms due to the phenomenon of *intermediate expression swell*, the price paid for freedom from roundoff error. The emphasis will be placed on efficient algorithms to compute exact Hermite

forms for polynomial matrices because this triangularization procedure is central to a large variety of algorithms important in the design of control and communication systems. Moreover, the triangular Hermite form is defined for any matrix with entries from a principal ideal ring and such matrices arise in many practical problems in communications and control, such as the design of convolutional coders and the analysis of quantization effects in linear systems. Due to their symbolic nature, our algorithms apply equally well to such problems since the particular ring involved in a problem can itself be considered as program input data.

Integrated Control-System Design via Generalized LQG (GLQG) Theory

Dr. Dennis S. Bernstein
Dr. David C. Hyland
Dr. Stephen Richter
Harris Corporation

Prof. Wassim M. Haddad
Department of Mechanical and
Aerospace Engineering
Florida Institute of Technology

Abstract

Thirty years of control systems research has produced an enormous body of theoretical results in feedback synthesis. Yet such results see relatively little practical application, and there remains an unsettling gap between classical single-loop techniques (Nyquist, Bode, root locus, pole placement) and modern multivariable approaches (LQG and H_∞ theory). Large scale, complex systems, such as high performance aircraft and flexible space structures, now demand efficient, reliable design of multivariable feedback controllers which optimally tradeoff performance against modeling accuracy, bandwidth, sensor noise, actuator power, and control law complexity. This presentation will describe a methodology which encompasses numerous practical design constraints within a single unified formulation. The approach, which is based upon coupled systems of modified Riccati and Lyapunov equations, encompasses time-domain linear-quadratic-Gaussian theory and frequency-domain H theory, as well as classical objectives such as gain and phase margin via the Nyquist circle criterion. In addition, this approach encompasses the optimal projection approach to reduced-order controller design. The current status of the overall theory will be reviewed including both continuous-time and discrete-time (sampled-data) formulations. The presentation will focus on the development of numerical algorithms for solving the coupled matrix equations which form the basis for the methodology.

Modern CACSD Using the Robust-Control Toolbox

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Abstract

The Robust-Control Toolbox [1] is a collection of 35 "M-files" which extend the capability of PC/PRO-MATLAB to do modern multivariable robust control system design. Included are continuous/discrete H^2/H^∞ synthesis tools, LQG Loop Transfer Recovery methods and a variety of model reduction techniques such as optimal Hankel, balanced truncation and balanced stochastic truncation, et cetera. In this paper, we will describe the capabilities of our toolbox and some illustrative examples to demonstrate the advantages of H^∞ loop-shaping over classical methods. Examples of model reduction for a large space structure will also be presented. Finally, we will describe some functions that recently have been developed for the toolbox as well as our plans for future enhancements.

[1] R. Y. Chiang and M. G. Safonov, Robust-Control Toolbox User's Guide, S. Natick, MA: MathWorks, Inc., 1988.

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H^2 and H^∞ - Design Tools for Linear Time-Invariant Systems

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Abstract

Recent advances in optimal control have brought design techniques based on optimization of H^2 and H^∞ norm criteria, closer to be attractive alternatives to single-loop design methods for linear time invariant systems. Significant steps forward in this technology are the deeper understanding of performance and robustness issues of these design procedures. However, acceptance of the technology has still been hindered by the lack of design tools that embed single-loop design formulation. Presented in this paper is a unique computer tool for designing low-order linear time-invariant controllers that addresses both performance and robustness issues via the familiar H^2 and H^∞ norm optimization. Application to flight control autopilot designs and control of flexible structures will be demonstrated.

An Algorithm for the Solution of Dynamic Linear Programs

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Abstract

The algorithm's objective is to speed up the solution of Dynamic Linear Programs (DLP) by a factor equal to the number of stages in the problem (a factor of 100 or more for many problems). This speed-up is measured in comparison to the time that a general active-set or simplex Linear Program (LP) solver would require to solve the same problem. This algorithm constitutes a stepping stone t an improved algorithm for solving Dynamic quadratic Programs, which, in turn, would make the nonlinear programming method of Successive Quadratic Programs (SQP) more practical for solving trajectory optimization problems. The ultimate goal is to bring trajectory optimization solution speeds into the realm of real-time control.

The algorithm exploits the banded nature of the large constraint matrix of the equality-constrained DLPs encountered when solving inequality-constrained DLPs by an active set approach. A numerically-stable, banded Q-R factorization of the banded constraint matrix is carried out starting from its last rows and columns. The active constraint set gets updated at intermediate stages of the factorization of the large constraint matrix via checking and updating of this set at current and subsequent stages when solving a smaller LP starting from a given stage. This is the equivalent of solving a time-varying, finite-horizon, discrete-time LQR problem by the backwards sweep method, except that the cost is linear and there are state and control inequality constraints. The algorithm in question might result in more changes of the active set than if the entire large constraint matrix were factored and had its factors updated for each change of the active set. The resulting cost of factor updates, on the other hand, may decrease dramatically. The usual stability of "closed-loop" Linear/Quadratic optimally-controlled systems, if it carries over to strictly linear cost

functions, may imply that the savings due to reduced factor update effort will outweigh the cost of an increased number of updates.

The paper will include computational results. Specifically, solution speed comparisons will be made between this algorithm and other algorithms that solve such LPs.

A Finite Element Based Method for Solution of Optimal Control Problems

Anthony J. Calise
Dewey H. Hodges
Georgia Institute of Technology
School of Aerospace Engineering

Abstract

This talk will present a finite element method for solving optimal control problems. The method is based on a mixed form of the Hamiltonian weak principle. The mixed form of this principle contains both states and costates as primary variables that are expanded in terms of nodal values and simple shape functions. Unlike other variational approaches to optimal control problems, however, time derivatives of the states and costates do not appear in the governing variational equation. Instead, the only quantities whose time derivative appear therein are virtual states and virtual costates. Numerical results will be presented for an elementary trajectory optimization problem which show excellent computational efficiency and self-starting capability.

The goal of this work is to evaluate the feasibility of this approach for general off-line optimization studies (which require minimal effort on the part of the user for set-up and execution), and for real time guidance of aerospace vehicles.

A Methodology for Formulating a Minimal Uncertainty Structure for Robust Control System Analysis

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Drexel University

Abstract

In the analysis of robust control systems for uncertain plants, the technique of formulating what is termed an "M-Δ structure" has become widely accepted and applied in the robust control literature. The "M" represents the transfer function matrix M(s) of the nominal system, and "Δ" represents an uncertainty matrix acting on M(s). The uncertainty can arise from various sources such as structured uncertainty from parameter variations or multiple unstructured uncertainties from unmodeled dynamics and other neglected phenomena. In general Δ is a block diagonal matrix, and for real parameter variations the diagonal elements are real. As stated in the literature, this structure can always be formed for any linear interconnection of inputs, outputs, transfer functions, parameter variations, and perturbations. However, very little of the literature addresses methods for obtaining this structure, and none of this literature (to the authors' knowledge) addresses a general methodology for obtaining a minimal M-Δ structure for a wide class of uncertainty. Since have a Δ matrix of minimum order would improve the efficiency of structured singular value (or multivariable stability margin) computations, a method of obtaining a minimal M-Δ structure would be useful. This paper presents a generalized method of obtaining a minimal M-Δ structure for systems with real parameter variations.

ILLUSTRATIVE DYNAMICAL SYSTEMS

Space Station Dynamics, Attitude Control and Momentum Management

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NASA-Johnson Space Center
Ramen P. Singh and Ravi Vengopal
Dynacs Engineering Co.

Abstract

The Space Station Attitude Control System software test-bed provides a rigorous environment for the design, development and functional verification of GN & C algorithms and software. All Space Station systems and sub-systems that are controlled or monitored by the GN & C software are simulated. The simulation presents a major computational challenge, starting from the simulation of full nonlinear flexible body dynamics including the orbital environment and Mobile Servicing System (MSS) operations, to task scheduling, sensor dynamics and inter-module communication. In addition, the complex tasks of providing flight algorithm sequencing and control and input command validation needs to be addressed.

This paper describes the approach taken for the simulation of the vehicle dynamics and environmental models using a computationally efficient algorithm. The simulation includes capabilities for docking/berthing dynamics, prescribed motion dynamics associated with the Mobile Remote Manipulator System (MRMS) and microgravity disturbances. The vehicle dynamics module interfaces with the test-bed through the centroal Communicator facility which is in trun driven by the Station Control Simulator (SCS) Executive. The Communicator addresses issues such as the interface between the discrete flight software and the continuous vehicle dynamics, and multi-programming aspects such as the complex flow of control in real-time programs. Combined with the flight software and redundancy management modules, the facility provides a flexible, user-oriented simulation platform.

Approximate Minimum-Time Trajectories
for
2-link Rigid and Flexible Manipulators

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Abstract

Powell's nonlinear programming code, VF02AD, has been used to generate approximate minimum-time trajectories for 2-link rigid manipulator movements in the horizontal plane. Constraints on the trajectory include boundary conditions on position and velocity, straight-line tracking between boundary positions, and motor torque limits. Trajectory results show an inner link torque profile with one switch. As the weight of the manipulator decrease, this torque profile approaches a bang-bang control. Verification of the trajectories has been accomplished with the ABAQUS code. An n-link finite-element model for a flexible manipulator for near real-time applications has been devised. Homotopy methods are being used to transition the minimum-time rigid body results to a 2-link flexible structure. Hardware is being fabricated to implement these results.

Modeling of Control Forces for Kinematical Constraints in the Dynamics of Multibody Systems-A New Approach

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Abstract

In many applications of multibody systems certain points are desired to follow prescribed paths, such as the end-effector in a robotic system. In such cases a common control problem is determination of the control forces that have be exerted by the actuators in the system to yield the prescribed motions. When these prescribed motions are treated as kinematical constraints on the multibody system then the system motion and the control forces can be determined.

The conventional solution procedure involves finding the generalized constraint reaction forces and then utilizing these or some equivalent form of them as the required control forces. On the other hand, since the constraint reaction forces are perpendicular to the constraint surfaces, the conventional solution procedure imposes an arbitrary restriction to the directions of the control forces.

In reality, depending on the actual places of the actuators in the system, one may want to achieve the prescribed kinematical constraints by control forces having different directions in relation to the constraint surfaces. In this paper a general control force representation for multibody systems dynamics subject to prescribed motions is introduced that replaces the constraint force representation. This enables solution of the system motion together with the corresponding control forces. Different selections of the control force directions are also discussed. Analysis of a redundant robot using various combinations of joint motors for prescribed end-effector motion is presented to illustrate the methods proposed.

Application of Numerical Optimization Techniques to Control System Design for Nonlinear Dynamic Models of Aircraft

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and
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Abstract

At high angles of attack, the aerodynamic forces and moments are, in general, time-dependent and nonlinear functions of motion variables. Therefore, the traditional control system design method based on a linearized dynamic system are not appropriate. In addition, the aerodynamic, kinematic, and inertial coupling phenomena are important to the high angle-of-attack flight dynamics of modern aircraft. Therefore, a suitable control system design method must be capable of incorporating these coupling phenomena with considerations of time-dependent, nonlinear aerodynamic forces and moments. In this proposed paper, a numerical optimization method to solve this problem will be described.

Methods in optimal control theory represent possible approaches to solving these problems under consideration. These methods are derived through calculus of variation. Another alternative is to apply numerical optimization techniques as are frequently used in structural and aerodynamic designs of large systems.

In the present method, a numerical optimization technique based on conjugate gradients and feasible directions (Ref. 1) is coupled with an analysis method which is to obtain numerical solutions of nonlinear 6 degree-of-freedom dynamic equations. This analysis method is to provide information needed in the design process, such a damping ratios, frequencies, motion variables involved in dynamic instabilities, etc. Since the analysis method ca deal with nonlinearities in the dynamics and the aerodynamics and with any general constraints on the control system configuration, the control system designed with a numerical optimization technique can be very realistic and effective.

Inverse Kinematics of Highly Redundant Variable-Geometry-Truss Manipulators

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University of Toronto

Abstract

A new class of robotic arm consists of a periodic sequence of truss substructures, each of which has several variable-length members. Such *variable-geometry-truss manipulators* (VGTMs) are inherently highly redundant and promise a significant increase in dexterity over conventional anthropomorphic manipulators. This dexterity may be exploited for both obstacle avoidance and controlled deployment in complex workspaces. The inverse kinematics problem for such unorthodox manipulators, however, becomes complex because of the large number of degrees of freedom, and conventional solutions to the inverse kinematics problem become inefficient because of the high degree of redundancy. This paper presents a solution to this problem based on a spline-like reference curve for the manipulator's shape. Such an approach has a number of advantages: (a) direct, intuitive manipulation of shape; (b) reduced calculation time; and (c) direct control over the effective degree of redundancy of the manipulator. Furthermore, although the algorithm has been developed primarily for variable-geometry-truss manipulators, it is general enough for application to a number of manipulator designs.

[a]Graduate Student
[b]Cockburn Professor

Determination of Joint Drives for Stable End-Effector Motion in Flexible Robotic Systems

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Abstract

The operation of high speed robots is severely limited by their manipulator dynamic deflection. The vibrations deteriorate the end-effector positional accuracy and reduce significantly the robot arm production rate. Hence determination of the appropriate control forces and torques at the joints to yield a stable end-effector motion is an important control problem.

The desired motion can be modeled as kinematical constraints and embedded into the governing equations of motion, from which one can solve the corresponding constraint reaction forces using classical methods. However the required joint forces and torques cannot be obtained from these forces due to the presence of elastic coordinates. For this reason previous solution procedures involved feedback and adaptive control algorithms which in tern increase the complexity of the problem considerably.

In this paper the conventional dynamical equations of motion for systems subject to kinematical constraints are modified by a new concept of control force representation. The directions of the control forces are selected such that they correspond to the joint degrees of freedom. The the joint control forces and torques that yield the unperturbed prescribed motion of the end-effector are solved simultaneously with the system motion. In the equations of motion all nonlinear interactions between the rigid and elastic motion are also automatically incorporated. A three-link manipulator is presented to illustrate the methods proposed.

Control of a Flexible Planar Truss Using Linear Proof Mass Actuators

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Daniel J. Inman
Professor
University at Buffalo

Abstract

The purpose of this work is to demonstrate the vibration suppression of a flexible truss by applying space realizable linear proof mass actuators (PMA's). The PMA's are attached to a flexible planar truss structure assembled in a "T" shape configuration, such that, the torsional as well as translational modes of vibration must be considered in the response of the structure. First, the PMA's are considered as traditional vibration absorbers, and are tuned to the translational and bending modes of interest. Second, structural sensor signals are used to generate a vibration suppression feedback control law to take advantage of the PMA's as inertial force generators. A reduced order FEM model of the structure is used to design the system's feedback control law. The feedback constants for the vibration suppression control law are calculated by applying an algorithm for optimal output feedback. This control law is then experimentally implemented on the truss/PMA system, and the response of the structure is evaluated to determine the performance of the active vibration suppression system and tuned proof mass actuators.

Simulation Studies Using Multibody Dynamics Code Dart

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Abstract

DART is a multibody dynamics code developed by Photon Research Associates for the Air Force Astronautics Laboratory (AFAL). The code is intended primarily to simulate the dynamics of large space structures, particularly during the deployment phase of their missions. DART integrates nonlinear equations of motion numerically. The number of bodies in the system being simulated is arbitrary. The bodies' interconnection joints can have an arbitrary number of degrees of freedom between 0 and 6. Motions across the joints can be large. Provision for simulating on-board control systems is provided. Conservation of energy and momentum, when applicable, are used to evaluate DART's performance.

After a brief description of DART, the paper describes studies made to test the program prior to its delivery to AFAL. Three studies are described. The first is a large angle reorientating of a flexible spacecraft consisting of a rigid central hub and four flexible booms. Reorientation was accomplished by a single-cycle sine wave shape torque input. In the second study, an appendage, mounted on a spacecraft, was slewed through a large angle. Four closed-loop control systems provided control of this appendage and of the spacecraft's attitude. The third study simulated the deployment of the rim of a bicycle wheel configuration large space structure. This system contained 18 bodies. An interesting and unexpected feature of the dynamics was a pulsing phenomena experienced by the stays whose playout was used to control the deployment.

The paper concludes with a short description of the current status of DART.

On Trajectory Generation for Flexible Space Crane: Inverse Dynamics Analysis by LATDYN

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Jet Propulsion Laboratory/California Institute of Technology
J. M. Housner
NASA Langley Research Center
S-C. Wu and C-W. Chang
The COMTEK Company

Abstract

For future in-space construction facility, one or more space cranes capable of manipulating and positioning large and massive spacecraft components will be needed. Because the space systems being constructed are relatively large and massive, the space cranes must have a reach on the order of 100-meter and be made of truss-type construction for structural efficiency. In order to optimize space crane's performance, an operational strategy consisting of gross-motion and fine-motion phases was proposed. Under this strategy, a space crane is commanded into position in a relatively fast pre-planned trajectory with relaxed requirements, and then "rigidized" by bracing against either the workpiece or an auxiliary support structure. After bracing, the subsequent fine motion will not involve the major crane bodies, and the precision movements between the workpieces can be performed without the adverse flexible crane body effect.

Inverse dynamics has been extensively studies as a basis for trajectory generation and control of robot manipulators. This paper will focus on trajectory generation in the gross-motion phase of space crane operation. Inverse dynamics of the flexible crane body is much more complex and intricate as compared with a rigid robot link. To model and solve the space crane's inverse dynamics problem, LATDYN program which employs a three-dimensional finite element formulation for the multibody truss-type structures will be used. The formulation is oriented toward a joint dominated structure which is suitable for the proposed space crane concept. To track a planned trajectory, procedures will be developed to obtain the actuation profile and dynamics envelope which are pertinent to the design and performance requirements of the space crane concept.

PARALLEL PROCESSING II

Characterization of Robotics Parallel Algorithms and Mapping onto a Reconfigurable SIMD Machine

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Purdue University

Abstract

The kinematics, dynamics, Jacobian, and their corresponding inverse computations are six major computational bottlenecks in the control of robot manipulators. Characteristics of various parallel algorithms for these computations are identified and analyzed. These characteristics include type of parallelism, degree of parallelism, uniformity of the operations, fundamental operations, data dependencies, and communication requirement. It is shown that most of the algorithms for robotic computations possess highly regular properties and some common structures, especially the linear recursive structure. Moreover, they are well-suited to be implemented on a single-instruction-stream multiple-data-stream (SIMD) computer with reconfigurable interconnection network. The model of a reconfigurable dual SIMD machine with internal direct feedback is introduced. A systematic procedure to map these robotic computations to the proposed SIMD machine is presented. A new scheduling problem for robotic computations on SIMD machines is investigated and a heuristic algorithm, called neighbourhood scheduling, that reorders the processing sequence of subtasks to reduce the communication time is also described. Mapping results of some robotic algorithms are discussed.

Concurrent Processing Simulation of the Space Station

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Abstract

This paper describes a demonstration of a temporal concurrent processing simulation of the Space Station undergoing a large - angle maneuver, which was performed under NASA Contract NAS9-17778. The concurrent processor used in this demonstration was the Custom Architectured Parallel Processing System (CAPPS), a loosely-coupled, multi-instruction - multi-data computer system, built and marketed by General Microelectronics Corporation (GMIC) of San Diego, California. The version of the CAPPS used in this demonstration included eight processors.

A novel methodology, involving an explicit (scalar) derivation (via symbol manipulation) of Kane's dynamical equations of motion, was employed in the preparation of the mathematical model. The Space Station is depicted as three flexible bodies interconnected at the two ALPHA gimbals to form a topological free configuration. The formulation accounts for the coupling of rigid-and flexible-body degrees-of-freedom and contains two separate control systems, one for maintaining the central body of the Space Station in a predetermined attitude control mode, and the other for performing large-angle rotations of the ALPHA gimbals.

The paper focuses on the development of an enabling, efficient computational load distribution methodology which balances the computation and effort among the eight processors of the CAPPS, and simultaneously seeks to minimize the interprocessor communication requirements.

The paper presents pertinent results of the concurrent processing simulation of the Space Station on the CAPPS. Speedup factors (the ratios of

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simulation times with one processor to those with N processors) are presented for various combinations of processors. The concurrent processing results are compared to sequential simulation results of the same mathematical model obtained on the IBM 3090, a state-of-the-art supercomputer.

A Decoupled Recursive Formulation of Flexible Multibody Systems for High Speed Dynamic Simulation

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Abstract

A new recursive dynamics algorithm for high speed computation is presented for flexible multibody systems. Kinematic relations between adjacent reference frames are used with a state vector notation that represents translational and rotational quantities simultaneously. Decoupled recursive equations of motion are first derived for a single chain multibody system. Equations of motion for a closed loop multibody system are next derived, using cut joint constraints. The algorithm is implemented on a shared memory multi-processor and a flexible multiple robot example is presented to demonstrated efficiency of the algorithm. A speed-up of a factor of 40 is demonstrated over a conventional Cartesian coordinate formulation, on a serial computer. An additional speed-up by a factor of 5 is demonstrated on an 8 processor parallel computer.

Algorithmic Considerations of Integrated Design for CSI on a Hypercube Computer Architecture

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Abstract

Issues related to accomplishing integrated design for structural and control systems are of increasing concern in the context of Large Space Structures. Indeed a number of attempts have been made to come up with unified cost criteria and optimization approaches ([1], [2]). It is evident that one of the major hurdles in all such attempts is, and is going to be, computational. For truly large scale systems all four aspects, namely finite element modeling, control algorithms, over-all optimization and finally total closed–loop simulation singly or jointly create computational problems.

The use of multiple processors connected in a hypercube topology has proven to be very useful in many large computation intensive tasks, especially with favorable parameter structures and algorithms which are compatible with the said topology. Indeed, all of the above four problems have been addressed individually (possibly in different contexts) for hypercube architectures. One can mention the work of the second author [3], where, as a result of finite element discretization, linear equations of banded form are obtained and solved with an approach based on the *Conjugate Gradient* method. Experimental results on a 16–node Intel 386–based iPSC/2 hypercube have shown an almost linear speedup over a single processor implementation.

Some control design related work, specifically on solutions of quadratic regulator problems have also been reported in the literature [4].

Yet these approaches have not been evaluated within the context of a total design package for Large Space Structures. In this paper we shall report on such an evaluation and introduce preliminary results for the development of a CSI design package which assumes a large system with subsystems under decentralized control. The decentralized control design

approach is based on the package DOLORES [5] which is being modified for hypercube implementation.

During this development, a distributed finite element modeling and control approach.

Parallel Computation of Large System Response with Substructuring and Occasional Reconciliation

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Abstract

Procedures are presented for computing transient response of large-scale systems on multiprocessors, where the parallelization is on the basis of a division of a system into subsystems, or substructures. Each processor computes response for a given subsystem independently, and occasionally the independently computed interface response histories are communicated among all processors for reconciliation. The procedure for reconciling independently computed subsystem responses is direct, rather than iterative, and can be done in such a way that the system dynamic equations are satisfied exactly at every time step. Alternatively, to save computation, subsystem interface responses can be sampled less frequently and interpolated so that system dynamic equations are satisfied exactly less frequently, but are very nearly satisfied over the entire time history. The merits of both approaches are investigated in this paper, and numerical examples are given. The methods presented have application in the analysis of complex structures and elastic multi-body systems.

Parallel Conjugate Gradient Algorithms for Manipulator Dynamic Simulation

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Abstract

In this paper parallel conjugate gradient algorithms for the computation of multibody dynamics are developed for the specialized case of a robot manipulator. For an n-dimensional positive-definite linear system, the Classical Conjugate Gradient (CCG) algorithms are guaranteed to converge in n iterations, each with a computation cost of $O(n)$; this leads to a total computational cost of $O(n^2)$ on a serial processor. We present conjugate gradient algorithms that provide greater efficiency cy using a preconditioner, which reduces the number of iterations required, and by exploting parallelism, which reduces the cost of each iteration. Two Preconditioned Conjugate Gradient (PCG) algorithms are proposed which respectively use a diagonal and a tridiagonal matrix, composed of the diagonal and tridiagonal elements of the mass matrix, as preconditioners. Parallel algorithms are developed to compute the preconditioners and their inversions in $O(\lceil \log_2 n \rceil)$ steps using n processors. A parallel algorithm is also presented which, on the same architecture, achieves the computational time of $O(\lceil \log_2 n \rceil)$ for each iteration. Simulation results for a seven degree-of-freedom manipulator are presented. Variants of the proposed algorithms are also developed which can be efficiently implemented on the Robot Mathematics Processor (RMP).

EMERGING INTEGRATED CAPABILITIES

Methodology for Analysis and Simulation of Large Multidisciplinary Problems

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Abstract

The Integrated Structural Modeling (ISM) program, under development with the Air Force Weapons Laboratory, is developing a multidisciplinary modeling and simulation environment for SDI applications. It combines modules from the disciplines of structures, controls, optics and thermal, with an integrating framework executive and database management system. Four areas of emphasis to be addressed in this paper are:

- Configuration Management
- Interdisciplinary data transfer
- Multiple discipline model synthesis
- Distributed processing computing environment.

Configuration management issues relate to the organization and control of software and technical solution paths. A common database handles model versions and facilitates interdisciplinary data transfer. Historically, model reduction in each area of analysis is completed before the disciplines are integrated together; however, there is a growing set of problems which demonstrate that model reduction on a component level will frequently lead to significant errors. Combining the various models before the process of model reduction eliminates this problem.

To conduct a time domain multidiscipline analysis several software modules will be combined into a single simulation. Integrating several disciplines in a high fidelity simulation will tax the resources of a single computer. distributed processing will be used to overcome this limitation. The paper will discuss these topics in greater detail and will illustrate where this approach has been successfully applied.

Enhanced Modeling features Within TREETOPS

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Abstract

TREETOPS is a non-linear time history simulation program developed under contract from Marshall Space Flight Center. TREETOPS originally provided a simulation environment that included control system interaction for flexible multibody spacecrafts and a linearization option.

Numerous extensions have been made to the original software. The purpose of this paper is to outline the features added to the TREETOPS environment. The additional features include a complete orbital environmental model including aerodynamic drag, gravity gradient and magnetic field models. The extensions include a set of actuator models for reaction wheels, single and double gimbal CMGs, motor drive actuators and magnetic torquers. The actuator models include non-linearities such as bearing friction, gear train backdrive and gear train compliance. Models for special devices such as cables, coulomb dampers, brakes, locks and hard-tops are available within the simulation. New features associated with manipulators have been added. These include a grappling feature to simulate the grasping of an object, and a Hertzian contact model to simulate the contact between the end-effector and a pre-defined surface.

In addition to the extensions to the time history simulation a number of interface programs and associated analysis tools have been integrated to form a complete TREETOPS modeling, control design and analysis package. This package includes a modal data preprocessor (TREEFLX), a model reduction package (TREESEL), a frequency response analysis package (CLASSIC), a linear system combination package (LINCOMB) and an eigen analysis program (EIGEN).

These additional features enhances TREETOPS' performance as a high fidelity analysis tool, yet retain its user friendly features.

Implementation of Generalized Optimality Criteria in a Multidisciplinary Environment

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Abstract for 3rd Annual Conference on aerospace Computational Control
28-30 August 1989
Oxnard, CA

Generalized Optimality Criteria methods can alleviate the computational burden of designing for many hundreds or thousands of design variables. The implementation in an Automated Structural Optimization System (ASTROS) for preliminary design of aerospace structures is described. Two algorithms are used: one using a compound scaling technique and another using dual mathematical programming methods. Both are applied to a swept wing model with constraints on its structural behavior and aerodynamic performance.

Neutral Particle Beam System Simulation

Jim Ryker and Don Washburn
R&D Associates

Abstract Not Available at Time of Printing

New Multivariable Capabilities of the INCA Program

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Christopher J. Thorpe,
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Abstract

The INteractive Controls Analysis (INCA) program was developed at the Goddard Space Flight Center to provide a user friendly, efficient environment for the design and analysis of control systems, specifically spacecraft control systems. Since its inception, INCA has found extensive use in the design, development, and analysis of control systems for spacecraft, instruments, robotics, and pointing systems. The INCA program was developed as a comprehensive classical design analysis tool for small and large order control systems. However, the latest version of INCA, expected to be released in September of 1989, has been expanded to include the capability to perform multivariable controls analysis and design. This current capability and our future plans will be discussed in this paper.

Multidisciplinary Expert-Aided Analysis and Design

Tom Hummel
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Abstract

The MEAD (Multidisciplinary Expert-Aided Analysis and Design) computer program was developed to support an environment in which integrated flight, propulsion, and structural control systems can be designed. The MEAD Computer Program (MCP) has several imbedded Computer-Aided Control Engineering (CACE) packages, a User Interface (UI), a Supervisor, a Data Base Management System (DBMS), and an Expert System (ES). The supervisor monitors and coordinates the utilization of the CACE packages, DBMS, ES, and UI. The user interface provides the capability for a novice as well as an expert to easily utilize the MCP effectively. The data-base management system tracks the control design process. The expert-aiding capability is used to alleviate the control engineer from much of the tedious and cumbersome iterative design process. This paper will discuss the current MCP 1.0 components and interfaces with a general description of their functionality.

Overview of Computational Control Research at UT Austin

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Abstract

An overview of current research activities at UT Austin is presented to discuss certain technical issues in the following areas:

- **Computer-Aided Nonlinear Control Design:** In this project, the describing function method is employed for the nonlinear control analysis and design of a flexible spacecraft equipped with pulse modulated reaction jets. INCA program has been enhanced to allow the numerical calculation of describing functions as well as the nonlinear limit cycle analysis capability in the frequency domain.

- **Robust LQG Compensator Synthesis:** Robust control design techniques and software tools are developed for flexible space structures with parameter uncertainty. In particular, an interactive, robust multivariable control design capability is being developed for INCA program.

- **LQR-Based Autonomous Control System for the Space Station:** In this project, real-time implementation of LQR-based autonomous control system is investigated for the space Station with time-varying inertias and with significant multibody dynamic interactions.

ASTEC — Controls Analysis for Personal Computers

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Abstract

The ASTEC (Analysis and Simulation Tools for Engineering Controls) software is underdevelopment at Goddard Space Flight Center (GSFC). The design goal is to provide a wide selection of controls analysis tools at the personal computer (IBM-PC and Macintosh) level, as well as the capability to upload compute-intensive jobs to a mainframe or supercomputer. The project is a follow-on to the INCA (INteractive Controls Analysis) [1] program that has been developed at CSFC over the past five years. While ASTEC makes use of the algorithms and expertise developed for the INCA program, the user interface has been redesigned to take advantage of the capabilities of the personal computer. This paper describes the design philosophy and the current capabilities of the ASTEC software.

JPL Control/Structure Interaction Design Environment

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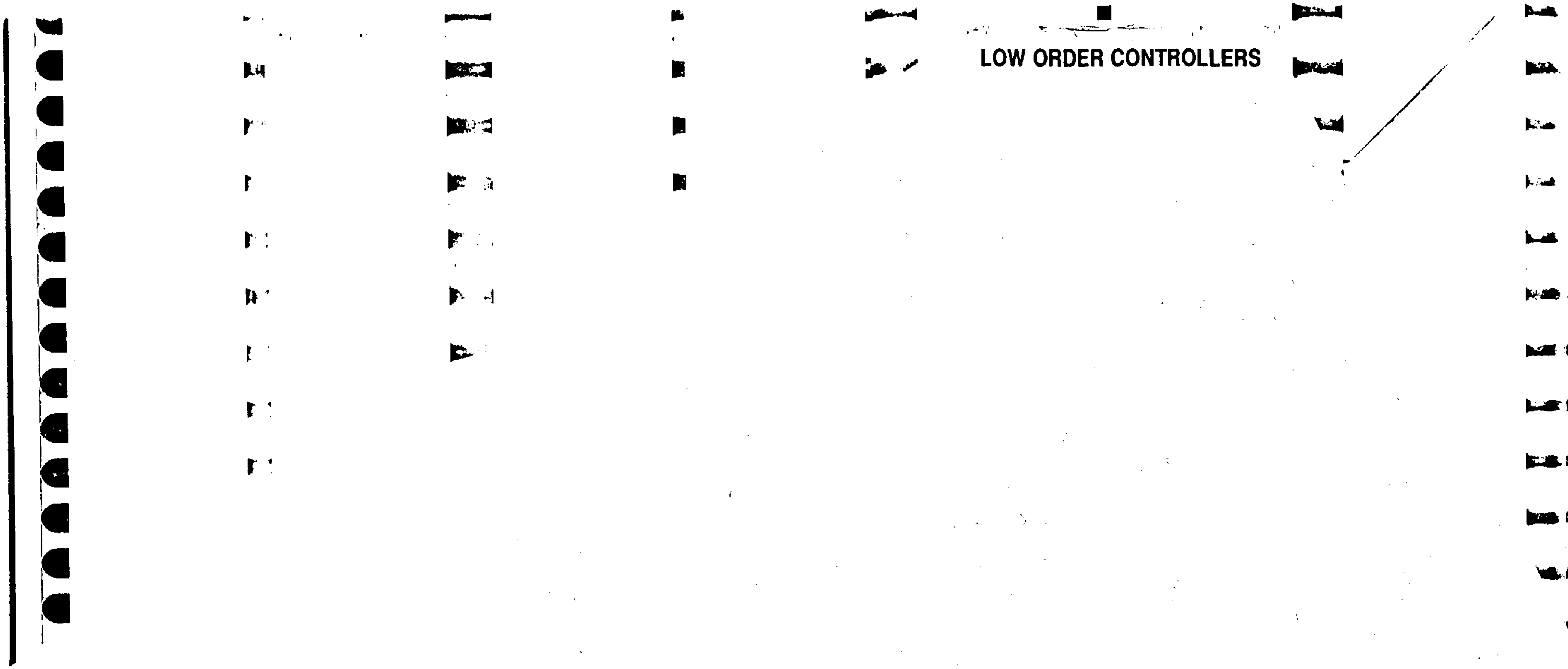
Abstract

Control/Structure Interactions is a technology program for spacecraft that exhibit interactions between the control system and structural dynamics. The program objectives include development and verification of new design concepts - such as active structure - and new tools - such as a combined structure and control optimization algorithm - and their verification in ground and possibly flight test. The new CSI design environment is centered around interdisciplinary engineers using new tools that closely integrate structures and controls. Verification is a central CSI theme and analysts will be closely integrated to the CSI Test Bed laboratory. Components, concepts, tools and algorithms will be developed and tested in the lab and in future Shuttle-based flight experiments.

The paper summarizes the design methodology by presenting block diagrams depicting the evolution of a spacecraft design and by describing analytical capabilities used in the process. The proposed multi-year JPL CSI implementation plan will be described along with the essentials of several new tools. A distributed network of computation servers and workstations has been proposed that will provide a state of the art development base for the CSI technologies.


LOW ORDER CONTROLLERS

Model Reduction for Flexible Spacecraft with Clustered Natural Frequencies

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Abstract for 3rd Annual Conference on Aerospace Computational Control
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Two approaches to the problem of modal reduction for flexible spacecraft that have proved very useful are balancing and modal truncation. Furthermore, it is well-known that a modal representation of a lightly damped flexible structure with widely-spaced natural frequencies is approximately balanced. Consequently, reduction in either coordinate system gives similar results for this case. It is important to note, however, that flexible space structures typically have clusters of closely-spaced frequencies. In such cases, reduction in modal coordinates can give large errors, while the error obtained using balancing is generally much smaller. A new reduction procedure which combines the best features of modal and balanced reduction is therefore developed in this paper. It is more efficient that balanced reduction of the full system, as it only involves balancing those subsystems of close modes that are highly correlated, yet is shown to yield results which are essentially as good.

Substructural Controller Synthesis (SCS)

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A decentralized design procedure called *substructural Controller Synthesis* (SCS) is proposed for the control design of flexible structures. The structure to be controlled is decomposed into several substructures by using a natural decomposition called *substructuring decomposition*. For each substructure , a subcontroller is designed by using the linear quadratic optimal control theory. Then, a global controller, which is to be employed to control the whole structure, is synthesized from the subcontrollers by using the same assembling scheme as that employed for the structure itself. Since the control design is carried out on the substructure level, the dimensionality of the computational problem associated with optimal control theory is substantially reduced. The dynamic models of the substructures do not have to be exact models and can be approximate (reduced-order) models obtained by the well-developed Component Mode Synthesis (CMS) method or by other model reduction methods. The SCS controller is a system controller, which means the control implementation is centralized. However, the control design is decentralized because the subcontroller for each substructure is designed independently. Due to this decentralized feature of control design, the SCS controller is expected to be less sensitive to plant change than a centralized control design. In fact, the SCS controller is an adaptive controller, which can be updated very economically if configuration or material properties of the structure change. A two-component plane-truss structure example is used to illustrate the efficacy of the proposed method.

Extensions of Output Variance Constrained Controllers to Hard Constraints

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Abstract

Covariance Controllers assign specified matrix values to the state covariance. a number of robustness results are directly related to the covariance matrix. This paper illustrates with examples the conservatism in known upperbounds on the H∞, L∞, and L_2 norms for stability and disturbance robustness of linear uncertain systems using covariance controllers. These results are illustrated for continuous and discrete time systems.

If

$$\dot{x}_p = A_p x_p + D_p w + B_p u, \qquad \dot{x}_c = A_c x_c + Fz$$

$$z = M_p x_p,\ y = C_p x_p \qquad u = Gx_c + H_z$$

describes a stable controllable linear system then the L∞ bound

$$\frac{\|y\|_\infty}{\|w\|_2} \le \bar{\sigma}(CXC^*) \quad , \qquad X \triangleq E\,[xx^*],\ x^* = (x_p^* x_c^*)$$

$$C = [C_p O]$$

holds for all L_2 disturbances w(t). If ΔA is the perturbation in A then A + ΔA remains stable for all ΔA subject to

$$\|\Delta A\| \le \frac{\underline{\sigma}(DWD^*)^{1/2}}{\bar{\sigma}(X(DWD^*)^{-1/2})}$$

The three assignability conditions for the closed loop to have the given covariance X are added to the robustness goals to complete the constraints on X to allow a specified degree of disturbance rejection

$$\frac{\|y\|_\infty}{\|w\|_2} \leq \varepsilon_1$$

and parameter tolerance

$$(\|\Delta A\|) \leq \varepsilon_2$$

for specified $\varepsilon_1, \varepsilon_2$.

Minimal Complexity Control Law Synthesis

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Abstract

In light of i) the increasingly complex nature of systems requiring controls and ii) the increasingly stringent accuracy required of control systems, the predominate considerations in control law design for modern engineering systems have become control law complexity and control law robustness, respectively. Indeed, with i) comes increasing and usually overriding concern with system cost, reliability, and maintainability, and with ii) comes increasingly complex control systems. Since, generally speaking, the more complex the control system, the more it costs, the less reliable it is, and the harder it is to maintain, it follows that i) and ii) conflict with each other through the specification of control system complexity. Similarly, with i) comes increasing levels of system/environmental uncertainty, and with ii) comes control systems which are increasingly robust relative to a fixed level of system/environmental uncertainty. Since the maximal achievable level of robustness decreases as the level of system/environmental uncertainty increases, it follows that i) and ii) are also in conflict with each other through the specification of control system robustness. correspondingly, control law complexity and control law robustness are, respectively, the predominant considerations in control law design for modern engineering systems.

In light of the above discussion, it seems both natural and appropriate to postulate the following paradigm for control law design for modern engineering systems. Minimize control law complexity subject to the achievement of a specified accuracy in the face of a specified level of

uncertainty. correspondingly, the overall goal in this paper is to make progress towards the development of a control law design methodology which supports this paradigm. We achieve this goal by developing a general theory of optimal constrained-structure dynamic output feedback compensation, where here constrained-structure means that the dynamic-structure (e.g., dynamic order, pole locations, zero locations, etc.) of the output feedback compensation is constrained in some way. By applying this theory in an innovative fashion, where here the indicated iteration occurs over the choice of the compensator dynamic-structure, the paradigm stated above can, in principle, be realized.

In this paper the optimal constrained-structure dynamic output feedback problem is formulated in general terms. an elegant method for reducing optimal constrained-structure dynamic output feedback problems to optimal static output feedback problems is then developed. This reduction procedure makes use of star products, linear fractional transformations, and linear fractional decompositions, and yields as a by-product a complete characterization of the class of optimal constrained-structure dynamic output feedback problems which can be reduced to optimal static output feedback problems. Issues such as operational/physical constraints, operating-point variations, and processor throughput/memory limitations are considered, and it is shown how anti-windup/bumpless transfer, gain-scheduling, and digital processor implementation can be facilitated by constraining the controller dynamic-structure in an appropriate fashion.

There are two principal contributions of this paper. First, many results on both full- and reduced-order optimal dynamic output feedback compensation obtained by other authors are readily shown to be but special cases of our results on optimal static output feedback compensation. As such, a significant unification of many known results in optimal control theory is achieved. Second, the general theory of optimal constrained-structure dynamic output feedback compensation provides a theoretical basis for the analytical design of optimal "industry standard" controllers, such as proportional-integral (PI) controllers and lead-lag compensators. consequently, the results presented in this series of papers will do much to help bridge the gap that currently exists between control theory and control practice.

OPTICON: Pro-Matlab Software for Large Order Controlled Structure Design

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Abstract

A software package for large order controlled structure design is described and demonstrated in this paper. The primary program, called OPTICON, uses both Pro-Matlab M-file routines and selected compiled Fortran routines linked into the Pro-Matlab structure. The program accepts structural model information in the form of state-space matrices and performs three basic design functions on the model: 1) open loop analyses, 2) closed loop reduced order controller synthesis, and 3) closed loop stability and performance assessment. The current controller synthesis methods which have been implemented in this software are based on the Generalized LQG theory of Bernstein. In particular, a reduced order Optimal Projection synthesis algorithm based on a homotopy solution method has been successfully applied to an experimental truss structure using a 58-state dynamic model. These results will be presented and discussed. The paper will also discuss current plans to expand the practical size of the design model to several hundred states and the intention to interface Pro-Matlab to a supercomputing environment.

Robust Fixed Order Dynamic Compensation for Large Space Structure Control

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Abstract

This talk will present a simple formulation for designing fixed order dynamic compensators which are robust to both uncertainty at the plant input and structured uncertainty in the plant dynamics. The emphasis is on designing low order compensators for systems of high order. The formulation is done in an output feedback setting which exploits an observer canonical form to represent the compensator dynamics. The formulation also precludes the use of direct feedback of the plant output. The main contribution lies in defining a method for penalizing the states of the plant and of the compensator, and for chosing the distribution on initial conditions so that the loop transfer matrix approximates that of a full-state design. To improve robustness to parameter uncertainty, the formulation avoids the introduction of sensitivity states, which has led to complex formulations in earlier studies where only structured uncertainty has been considered.

The usefulness of the design approach is illustrated by an example for high bandwidth pointing control of a flexible spacecraft structure.

Multivariable Frequency-Weighted Order Reduction Algorithm for Control Synthesis

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Abstract

Model or controller order reduction for closed-loop analysis and synthesis is considered. An algebraic framework utilizing projection operators is discussed, two reduction methods originally motivated in the time domain are examined, and their ties to the frequency domain explored. causes for failure of these techniques to provide stable reduced-order compensators are established. Frequency-weighted techniques are introduced, and guidelines for weighting selection discussed. Properties of he frequency-weighted results are noted, and an example clearly illustrates the effects of frequency weighting. The technique is consistent with classical, intuitive approaches; is directly generalized to multivariable, singular-value theory; and an efficient numerical algorithm is presented.

Distributed Neural Control of a Hexapod Walking Vehicle

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Abstract

There has been a long-standing interest in the design of controllers for multilegged vehicles. Our approach is to apply distributed control to this problem, rather than using parallel computing of a centralized algorithm. We describe a distributed neural network controller for hexapod locomotion which is based on the neural control of locomotion in six-legged insects. Through simulation we have demonstrated that this controller can generate a continuous range of statically stable gaits at different speeds by varying a single control parameter. In addition, the controller is extremely robust, and can continue to function even after several of its elements have been disabled. We are building a small hexapod robot whose locomotion will be controlled by this network. We intend to extend our model to the control of legs with redundant degrees of freedom by using data on the control of multisegmented insect legs. Our combination of robotics, computer modelling, and neurobiology has been remarkably fruitful, and is likely to lead to deeper insights into the problems of real-time sensorimotor control.

REAL TIME SIMULATION

Combining High Performance Simulation, Data Acquisition and Graphics Display Computers

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Abstract

For a growing class of simulation problems, the generation of the motion and signal environment for testing hardware-in-loop requires high speed computing along with data transfer, mass storage, and graphic display rates sufficient to save and display the data generated. This typically requires a complex of specialized processors that are specifically selected for their processing tasks, along with a specialized communication computer system for fast interprocessor communication and data transfer.

This computer complex is typically employed in different roles as the test hardware-in-loop interface matures during an advanced development or full-scale engineering development program. Early in such a program, all elements of the system to be studied (and their environments) are simulated. then as in-loop elements are developed, they are inserted into the complex, and the simulation computers concentrate on increasing the fidelity of the test environment dynamics that the in-loop elements experience.

This paper discusses issues involved in the continuing development of an advanced all-digital simulation computer complex (Hickman, 87, 88). This approach provides the capability to perform the majority of tests on advanced systems, non-destructively. The controlled test environments can be replicated to examine the response of the systems under test to alternative treatments of the system control design, or test the function and qualification of specific hardware. field tests verify that the elements simulated in the laboratories are sufficient.

The digital computer complex is hosted by a digital Equipment Corp. MicroVAX computer with an Aptec computer Systems Model 24 /O computer performing the communication function. an Applied Dynamics International AD100 performs the high-speed simulation computing and an Evans and Sutherland PS350 performs on-line graphics display. A Scientific Computer Systems SC340 acts as a high-performance Fortran

files from programs coded in Fortran that are required for the real-time processing.

Four programming languages are involved in the process, FORTRAN, ADSIM, ADRIO, and STAPLE. FORTRAN is employed on the MicroVAX host to initialize and terminate the simulation runs on the system. The generation of the data files on the SCS40 also is performed with FORTRAN programs. ADSIM and ADRIO are used to program the processing elements of the AD100 and its IOCP processor. STAPLE is used to program the Aptec DIP and DIA processors.

Man-in-the-Control-Loop Simulation of Manipulators

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Abstract

Two manipulators are simulated with an operator in the control loop: J. I. Case 580K backhoe, and Robotics Research Corporation (RRC) robot arm. The operator's control action is converted into analogue signals, then digitized and interfaced with computer simulation and graphics software. In this setup, there are three essential components: hardware interface device, dynamics simulation and graphics software, and a human operator.

The backhoe is a four degree-of-freedom (dof) manipulator with independently-controlled hydraulic actuators. Using two 2-axis joysticks, the operator controls, in an open-loop manner, spool valve displacements that in turn control hydraulic force outputs.

The RRC arm is a seven dof manipulator with direct drive, independently-controlled joint motors. and each joint has its own closed-loop controller, so the system is basically position-controlled. The teleoperation of the RRC arm is simulated with an operator in the control loop through the interface with two 3-axis joysticks and with Kraft mini-master that provides tactile feedback.

A New Second-Order Integration Algorithm for Simulating Mechanical Dynamic Systems

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Abstract

A new integration algorithm which has the simplicity of Euler integration but exhibits second-order accuracy is described. In fixed-step numerical integration of differential equations describing mechanical dynamic systems the method represents displacement and acceleration variables at integer step times and velocity variables at half-integer step times. asymptotic accuracy of the algorithm is twice that of trapezoidal integration and ten times that of second-order Adams-Bashforth integration. The algorithm is also compatible with real-time inputs when used for a real-time simulation. It can be used to produce simulation outputs at double the integration frame rate, i.e., at both half-integer and integer times, even though it requires only one evaluation of state-variable derivatives per integration step. The new algorithm is shown to be especially effective in the simulation of lightly-damped structural modes. Both time-domain and frequency-domain accuracy comparisons with traditional integration methods are presented. Stability of the new algorithm is also examined.

The Use of Real-Time, Hardware-in-the-Loop Simulation in the Design and Development of the New Hughes HS601 Spacecraft Attitude Control System

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Hughes Aircraft Company, Space and Communications Group

Abstract

Realtime simulation and hardware-in-the-loop testing is being used extensively in all phases of the design, development, and testing of the attitude control system (ACS) for the new Hughes HS601 satellite bus. Realtime, hardware-in-the-loop simulation, integrated with traditional analysis and pure simulation activities is shown to provide a highly efficient and productive overall development program. Implementation of high fidelity simulations of the satellite dynamics and control system algorithms, capable of real-time execution (using applied Dynamics International's System 100), provides a tool which is capable of being integrated with the critical flight microprocessor to create a 'mixed simulation' test (MST). The MST creates a highly accurate, detailed simulated on-orbit test environment, capable of open and closed loop ACS testing, in which the ACS design can be validated. the MST is shown to provide a valuable extension of traditional test methods. a description of the MST configuration is presented, including the spacecraft dynamics simulation model, sensor and actuator emulators, and the test support system. Overall system performance parameters are presented. MST applications are discussed - supporting ACS design, developing on-orbit system performance predictions, flight software development and qualification testing (augmenting the traditional 'software-based' testing), mission planning, and a cost-effective subsystem-level acceptance test. The MST is shown to provide an ideal tool in which the ACS designer can 'fly the spacecraft on the ground'.

"A Real Time, FEM Based Optimal Control Algorithm and its Implementation Using Parallel Processing Hardware (Transistors) in a μ Processor Environment"

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Abstract

There is an evident need to discover a means of establishing reliable, implementable controls for systems that are plagued by nonlinear and, or uncertain, model dynamics. There is reported here the development of a generic controller design tool for tough-to-control systems. the method utilizes a moving grid, time finite element based solution of the necessary conditions that describe an optimal controller for a system.

The technique produces a discrete feedback controller. Real time laboratory experiments are now being conducted to demonstrate the viability of the method. The algorithm that results is being implemented in a microprocessor environment. Critical computational tasks are accomplished using a low cost, on board, multiprocessor (INMOS T800 Transputers) and parallel processing. Progress that has been made to date to validate the methodology will be presented. applications of the technique to the control of highly flexible robotic appendages will be suggested.

Six-Degree-of-Freedom Aircraft Simulation Using the ADI AD 100 Digital Computer and ADSIM Simulation Language

Clare Savaglio
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Abstract

This paper presents a realistic simulation of an aircraft in flight using the AD100 digital computer and ADSIM simulation language. The aircraft model, which is representative of atypical business jet, is modelled with six-degrees-of-freedom. The simulation evaluates a large aerodynamic data base (130,000 function values) using function interpolation to obtain the aerodynamic coefficients. A flight control system allows the aircraft to be partially or fully "flown" under autopilot control.

An additional feature of this simulation is the implementation of a digital flight control system. Continuous time systems are normally modelled using the Laplace transform, while discrete time systems can be defined using z-transform theory. The continuous time system derivatives will be integrated using one of the many available numerical integration schemes. ADSIM supports thirteen such numerical integration methods. The discrete time system will be converted from the z-transform representation t a data sequence which is represented mathematically in time as a set of difference equations.

The ADSIM language can support both the continuous and discrete time system data types. Using ADSIM, two dynamic blocks may be defined; one dynamic block would contain the continuous time system ordinary differential and algebraic equations (dynamic continuous) while the second dynamic block would contain the discrete time system difference and algebraic equations (dynamic discrete).

A special simulation control structure has been created in order to implement the simulation of this mixed-data system. The ADSIM simulation executives are easily modified in order to execute the dynamic blocks in the desired order. for example, when simulating a mixed-data system it is necessary to execute the continuous portion of the system n times relative to the execution of the discrete system, where $n * dt$ is the

sample period of the digital controller and *dt* is the integration step size of the continuous portion of the simulation.

The simulation also includes the option to trim the aircraft in longitudinal flight, given the aircraft velocity and altitude. the AD100 computing time for a single pass through the dynamic equations is 137.5 microseconds.

This paper discusses the use of the applied Dynamics Simulation (ADSIM) language for the simulation of a six-degree-of-freedom aircraft. simulation results will be discussed.

Six-Degree-of-Freedom Missile Simulation Using the ADI AD100 Digital Computer and ADSIM Simulation Language

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Abstract

This paper illustrates the use of an AD100 computer and ADSIM language in the six-degree-of-freedom digital simulation of an air-to-ground missile. The missile is launched from a moving platform, typically a helicopter and is capable of striking a mobile target up to 33,000 feet away. The missile is controlled by four fins mounted in cruciform configuration at the rear of the missile. The fins are independently controlled by pneumatic servos. The servos are activated by commands from the autopilot which processes the sensor and seeker guidance outputs before issuing these commands. The missile roll, pitch, and yaw attitudes are sensed using the required two-degree-of-freedom gyros. The target is tracked using an inertially stabilized seeker (LASER or RF/IR) mounted at the front end of the missile inside a radome. Imperfect attitude sensing and target tracking are included in the simulation. The user can exclude or include (amplify) these extraneous effects by selecting the proper option switches.

Function generation is used to determine the multivariable aerodynamic coefficients, rotor downwash (the effects of which are confined to the neighborhood of the helicopter), instantaneous thrust, gyro drift angles, and seeker tracking errors.

ADSIM is a block structured language. ADSIM supports FORTRAN blocks which may contain user written FORTRAN for pre/post run calculations. Procedural run-time code may appear in blocks called REGIONS. DYNAMIC blocks are non-procedural in the sense that they are sorted to define the correct order of execution for the dynamic equations. for large simulations, detection of algebraic loops can be a difficult process and many simulations, especially those written in languages such as FORTRAN, have many algebraic loops which are entirely undetectable. ADSIM FUNCTIONS and MODELS are user written macros that define systems or subsystems that appear repeatedly in a simulation. Macros

differ from subroutines in that macros are expanded in line in a particular block of code. While this process uses more system memory, it minimizes costly overheads involved in calling subroutines. The functions and models can be placed into an ADSIM library for easy access to a large number of ADSIM users. The ADSIM language also supports all normal standard functions as well as functions for multivariable function generation (up to functions of seven independent variables), control system non-linearities, (hysteresis, dead zone and much more) and system models such as limited integrators and quaternions.

The ADSIM compiler can generate code for execution of the simulation on either the AD100 (a parallel processing computer for real-time hardware-in-the-loop simulation) or on one of the DEC VAX family of general purpose computers.

The user communicates with the program at run-time using INTERACT, a utility designed by Applied Dynamics International (ADI). a rich set of INTERACT commands allow the user to change any simulation variable or to change the integration time step and method; an on-line data logger and graphics package also allow the capability to verify simulation results. Various researchers have estimated that the verification and validation portion of a simulation can consume 30 to 60 percent of a particular project's schedule and budget. The interactive nature of ADSIM, together with the INTERACT utility, can make the task of verification and validation easier and allow one to develop a feel for the system being simulated.

This paper discusses the use of the ADSIM language for the simulation of a six-degree-of-freedom missile. simulation results will be presented.

Real-Time Closed-Loop Simulation and Performance Evaluation of Control Systems in Harsh Electromagnetic Environments

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Abstract

Control systems for applications such as aircraft avionics and multibody systems must maintain adequate control integrity in adverse as well as nominal operating conditions. For example, control systems for advanced aircraft with relaxed static stability will be critical to flight and will, therefore, have very high reliability specifications which must be met regardless of operating conditions. In addition, multibody systems such as robotic manipulators performing critical functions must have control systems capable of robust performance in any operating environment in order to complete the assigned task reliably. Severe operating conditions for electronic control systems can result from electromagnetic disturbances caused by lightning, high energy radio frequency (HERF) transmitters, and nuclear electromagnetic pulses (NEMP). For this reason, techniques must be developed to evaluate the integrity of the control system in adverse operating environments. The most difficult nd illusive perturbations to computer-based control systems that can be caused by an electromagnetic environment (EME) are functional error modes that involve no component damage. These error modes are collectively known as "upset", can occur simultaneously in all of the channels of a redundant control system, and are software dependent. Upset studies performed to date have not addressed the assessment of multi-channel systems and do not involve the evaluation of a control system operating in a closed-loop with the plant. This paper presents a methodology for performing a real-time simulation of the closed-loop dynamics of a multi-channel control system with a simulated plant operating in an electromagnetically harsh environment. In particular, the paper discusses considerations for performing upset tests on the controller. some of these considerations are the generation and coupling of analog signals representative of electromagnetic disturbances to a control system under test, analog data acquisition, an digital data

acquisition from multi-channel systems. In addition, the paper presents a case study of an upset test methodology for a fault tolerant electronic aircraft engine control system.

MBODY COMPONENT
REPRESENTATION

Multibody Dynamics: Modeling Component Flexibility with Fixed, Free, Loaded, Constraint, and Residual Modes

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Abstract

The assumed-modes method in multibody dynamics allows the elastic deformation of each component in the system to be approximated by a sum of products of spatial and temporal functions commonly known as modes and modal coordinates respectively. This paper focuses on the choice of component modes used to model articulating and non-articulating flexible multibody systems. Attention is directed toward three classical Component Mode Synthesis (CMS) methods whereby component normal modes are generated by treating the component interface (I/F) as either fixed, free, or loaded with mass and stiffness contributions from the remaining components. The fixed and free I/F normal modes are augmented by constraint and residual modes respectively such that the resulting component mode sets are statically complete with respect to I/F forces. In this paper a mode selection procedure is outlined whereby component modes are selected from the Craig-Bampton (fixed I/F plus constraint), McNeal-Rubin (free I/F plus residual), and Benfield-Hruda (loaded I/F) mode sets in accordance with a modal ordering scheme derived from balanced realization theory. The success of the approach is judged by comparing the actuator-to-sensor frequency response of the reduced order system with that of the full order system. For articulating structures, the frequency response comparison is done over several "frozen" system configurations and over the frequency range of interest. A step-by-step example demonstrate the effectiveness of the proposed mode selection method.

Component Model Reduction Via the Projection and Assembly Method

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Abstract

The problem of acquiring a simple but sufficiently accurate model of a dynamic system is made more difficult when the dynamic system of interest is a multibody system comprised of several components. A low order system model may be created by reducing the order of the component models and making use of various available multibody dynamics programs to assemble them into a system model. The difficulty is in choosing the reduced order component models to meet system level requirements. The projection and assembly method, proposed originally by Eke, solves this difficulty by forming the full order system model, performing model reduction at the system level using system level requirements, and then projecting the desired modes onto the components for component level model reduction. In this paper, the projection and assembly method is analyzed to show the conditions under which the desired modes are captured exactly - to the numerical precision of the algorithm.

Model Reduction in the Physical Coordinate System

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Abstract

In the dynamics modeling of a flexible structure, finite element analysis employs reduction techniques, such as Guyan's reduction, to remove some of the "insignificant" physical coordinates, thus producing a dynamics model that has smaller mass and stiffness matrices. But this reduction is limited in the sense that it removes certain degrees of freedom at a node point, instead of node points themselves in the model. From the standpoint of linear control design, the resultant model is still too large despite the reduction. Thus, some form of model reduction is frequently used in the control design by approximating a large dynamical system with a fewer number of state variable. However, a problem arises from the placement of sensors and actuators in the reduced model, because a model usually undergoes, before being reduced, some form of coordinated transformations that do not preserve the physical meanings of the states. To correct such a problem, a method is developed that expresses a reduced model in terms of a subset of the original states.

The proposed method starts with a dynamic model that is originated and reduced in finite element analysis. Then the model is converted to the state space form, and reduced again by the internal balancing method. At this point, being in the balanced coordinate system, the states in the reduced model have no apparent resemblance to those of the original model. Through another coordinate transformation that is developed in this paper, however, this reduced model is expressed by a subset of the original states.

The procedure is illustrated with two examples: One starts with a finite element model and finally arrives at the reduced model that has a fewer number of node points. The other example is on low-order state estimator design based on the reduced model that is produced by the proposed method.

Determination of Damping Matrices for Components of Large Structures

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Abstract

The paper focuses attention on a mechanical system comprising several interconnected bodies some or all of which are flexible. It is assumed that the form (usually diagonal) and contents of the system damping matrix are given. Procedures are then presented for generating the damping matrices that must be assigned to the components of the given system, so that the resulting system damping matrix is identical to the given one. Simple examples are used to illustrate the effectiveness of the method. Such procedures will be of inestimable value when using DISCOS or similar multibody simulation tools to study the dynamics of interconnected flexible bodies. They will also be of value in the study of large structures where one is often compelled to break the structure down into components that are then assigned to different analysis.

Modal Identities for Multibody Elastic Spacecraft Using Appendage Modes, Hinges-Free and Hinges-Locked Vehicle Modes

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Abstract

This paper answers the question: Which set of modes furnishes a higher fidelity math model of dynamics of a multibody, deformable spacecraft–hinges-free or hinges-locked vehicle modes? Three sets of general, discretized, linear equations of motion of a spacecraft with an arbitrary number of deformable appendages, each articulated directly to the core body, are obtained using the above two families of modes and appendage modes. By a comparison of these equations, eleven sets of matrix modal identities are constructed which involve modal momenta coefficients and frequencies associated with the three classes of modes. the sums of infinite series that appear in the identities are obtained in terms of mass, and first and second moments of inertia of the appendages, core body, and vehicle by using some basic identifies concerning appendage modes. Applying the above identities to a four-body spacecraft, the hinges-locked vehicle modes are found to yield a higher fidelity model than hinges-free modes, because the hinges-free modes have nondiminishing modal coefficients whereas the hinges-locked modes have modal angular momentum coefficients diminishing rapidly with frequency. These characteristics are proved and illustrated in the paper.

Issues in CSI Analysis for Large Scale Systems

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Abstract

Future spacecraft such as the International Space Station result in flexible models with hundreds, or perhaps thousands of modes in a frequency range where the potential for control/structure interaction exists. This provides the analyst with a formidable model reduction problem at both the component and the system level. Approaches to dealing with this problem, including issues associated with using normal modes as a structural representation, applicability of alternate structural representations and algorithms for selecting "important" modal degrees of freedom at both the component and the system level will be discussed. Practical implementation of these techniques on a large scale model of the Space Station will be presented.

Structural Modeling for Control Design (Articulated Multibody Component Representation)

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Abstract

High frequency, high gain flexible responses in gimbaled multibody systems are discussed. Their origin and physical significance are explained in terms of detailed mass and stiffness modeling at sensor/actuator interfaces. Their behavior in dynamical models is explained in terms of the structural freedoms used in control-structure-interaction analysis. Guyan Reduction, Generalized Dynamic Reduction, inadequate detailed mass modeling, as well as system mode truncation, are shown to eliminate the high frequency high gain response, and therefore to lose system flexibility often important for stability and performance predictions. Model validation by modal survey testing is shown to risk similar loss of accuracy. The difficulties caused by high frequency responses in component mode simulations, such as DISCOS, and also linearized system mode simulations, are described, and approaches for handling these difficulties are discussed.

Significance of Norms and Completeness in Variationally Based Methods

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Abstract

Virtually all flexible multibody codes in use today are based upon some variational principle of mechanics. The most common of these being Hamilton's Principle and its discretized version – Lagrange's Equations. Regardless of the particular label attached to the technique (e.g., assumed modes method, Ritz-Galerkin), the problem reduces to rendering stationary a certain definite integral with respect to a sufficiently regular family of functions subject to certain "geometric" boundary conditions. In practice the basis functions are generated using a general purpose finite element program and may be subject to further manipulation such as modal synthesis before being incorporated into the multibody program. It is assumed by many analysts that the basis functions used are to a certain extent arbitrary. It is argued that so long as they are members of an infinite family of orthogonal functions and satisfy the geometric boundary conditions, convergence of the dynamic response is guaranteed. Some analysts with better memories will recite an additional caveat dealing with "completeness" but when pressed, fail to support their statements with rigorous proof.

The purpose of this paper is to focus attention on an important condition which is often overlooked in practice: the completeness of the basis functions in an appropriate inner product space. By means of a simple problem - the static deformation of a beam under uniform loading, it is shown that erroneous results can be obtained if the basis functions used in the expansion of the elastic displacement field are not complete with respect t an appropriate norm. It is extremely significant that the variational principle using an inappropriate set of basis functions is convergent, but to an erroneous result. This would be extremely difficult if not impossible to identify in a typical spacecraft application. Finally, some results enforcing

satisfaction of natural boundary conditions in the finite Element method are presented.

USER ENVIRONMENT

The Power and Efficiency of Advanced Software and Parallel Processing

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Lawrence W. Taylor, Jr., NASA Langley Research Center

Abstract

Real-time simulation of flexible and articulating systems is difficult because of the computational burden of the time varying calculations. The mobile servicing system of the NASA Space Station Freedom will handle heavy payloads by local arm manipulations and by translating along the spline of the Station. Because such motion can be very disruptive to the attitude of the Space Station, it is crucial to have real-time simulation available.

To enable such a simulation to be of high fidelity and to be able to be hosted on a modest computer, special care must be made in formulating the structural dynamics. frontal solution algorithms save considerable time in performing these calculations. In addition, it is necessary to take advantage of parallel processing, and in particular, certain powerful processors available at modest cost. It is crucial that both the algorithm and the parallel processing be compatible to take full advantage of both. an approach is offered which will result in high fidelity, real-time simulation for flexible, articulating systems such as the space Station remote servicing system.

Advanced Software for Design

Robert Kosut
Integrated Systems Inc

Abstract not available at time of printing

Design Tools for Real World Problems

Dave Hyland
Harris Corporation

Abstract not available at time of printing

Simulation Analysis of Control-Structure Interaction (CSI) Using the LATDYN Computer Code

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COMTEK

Abstract

A general-purpose multibody dynamic analysis code LATDYN is used to investigate the CSI phase-0 revolutionary model. LATDYN is an acronym for Large Angle Transient DYNamics, a 3-D public domain research code which is designed for modelling space structures as well as their control systems. Unlike most of the existing formulations which superimpose elastic mode shapes onto rigid references, LATDYN is finite element based. The displacements and velocities of each grid point are used as state variables to describe the total performance of the system. Instead of using constraint equations to define joint connections in the system, in LATDYN's formulation, the joint kinematics is taken into consideration when deriving the equations of motion, and joint degrees of freedom are included in the model explicitly. This provides a user-oriented simulation tool for control investigations. In this paper, three different control systems are applied on the CSI structure, and numerical results are presented.

Control Design for Aerospace Systems Modeled Using ADAMS

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Abstract

This paper presents a technique for control design and simulation using the ADAMS software. ADAMS is a commercial software package for modeling and large displacement simulation of nonlinear mechanical systems.

To design control systems for ADAMS models, requires that a minimum realization linear time invariant (LTI), state space representation of the ADAMS models be obtained. This functionality has been recently provided in the ADAMS family of software products. This state space LTI representation can be produced in formats for input to several commercial control design packages. The user can exercise various design strategies in the control design software to arrive at a suitable controller.

The control design is then incorporated into the open loop model to arrive at the closed loop ADAMS model with feedback. This model can now be simulated in ADAMS to evaluate its performance.

Multibody Dynamics Model Building Using Graphical Interfaces

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Abstract

In recent years, the extremely laborious task of manually deriving equations of motion for the simulation of multibody spacecraft dynamics has largely been eliminated. Instead, the dynamicist now works with commonly available general purpose dynamics simulation programs which generate the equations of motion either explicitly or implicitly via computer codes. The user interface to these programs has largely been via input data files, each with its own required format and peculiarities, causing errors and frustrations during program setup. This paper describes recent progress in a more natural method of data input for dynamics programs: the graphical interface. Also discussed is a PC based animation program for depicting results of rigid multibody spacecraft dynamics simulation.

DISTRIBUTED PARAMETER
TECHNIQUES

Controlling Flexible Structures with Second Order Actuator Dynamics

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Abstract

This paper examines the control of flexible structures for those systems with actuators that are modeled by second order actuator dynamics. The modeling procedure suggested here uses a continuum model of the flexible structure to be controlled, coupled with lumped parameters second order dynamic models of the actuators performing the control. This model is appropriate for instance, in the modeling of the control of a flexible panel by proof-mass actuators as well as other beam, plate and shell like structural member. This hybrid lumped/continuum model is used to discuss the differences between modal approximations, Galerkin approximations and computation of the controlled response by using a fully distributed Green's function model.

Space Applications of Distributed Parameter Techniques

Donald Washburn
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Abstract not available at time of printing

Numerical Algorithms for Computations of Feedback Laws Arising in Control of Flexible Systems

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Abstract

Several continuous models will be examined, which describe flexible structures with boundary or point control/observation. The main goal of the talk is to discus issues related to the computation of feedback laws (particularly stabilizing feedbacks) with sensors and actuators located either on the boundary or at specific point locations of the structure.

One of the main difficulties is due to the great sensitivity of the system (hyperbolic systems with unbounded control actions), with respect to perturbations caused either by uncertainty of the model or by the errors introduced in implementing numerical algorithms. Thus, special care must be taken in the choice of the appropriate numerical schemes which eventually lead to implementable finite dimensional solutions. Finite dimensional algorithms will be constructed on a basis of a priori analysis of the properties of the original, continuous (infinite diversional) systems with the following criteria in mind:

(1) convergence and stability of the algorithms

(2) robustness - reasonable insensitivity with respect to the unknown parameters of the systems.

Examples with mixed finite element methods and spectral methods will be provided.

A Theory of Nonlinear Damping in Flexible Structures

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Abstract unavailable at time of printing

Modeling and Control of Flexible Space Structures

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Abstract

Large orbiting space structures are expected to experience mechanical vibrations arising from several disturbing forces such as those induced by shuttle takeoff or docking and crew movements. In this paper, we consider the problem of modeling and control of large space structures subject to these and other disturbing forces. The system consists of a (rigid) massive body, which may play the role of experimental modules located at the center of the space station and flexible configurations, consisting of several beams, forming the space structure. A complete dynamic model of the system has been developed using Hamilton's principle. This model consists of radial equations describing the translational motion of the central body, rotational equations describing the attitude motions of the body and several beam equations governing the vibration of the flexible members (platform) including appropriate boundary conditions. In summary the dynamics of the space structure is governed by a complex system of interconnected partial and ordinary differential equations.

Using Lyapunov's approach the asymptotic stability of the space structure is investigated. For asymptotic stability of the rest state (nominal trajectory) we have suggested feedback controls. In our investigation stability of the slewing maneuvers is also considered.

Several numerical results are presented for illustration of the impact of coupling and the effectiveness of the stabilizing controls. This study is expected to provide some insight into the complexity of modeling, analysis and stabilization of actual space structures.

Mini-Mast Dynamic Analysis Using the Truss-Beam Model

Elias G. Abu-Saba
William M. McGinley
Raymond C. Montgomery

Abstract

The Mini-Mast is a generic space truss designed by Astro Aerospace Corporation of California. A truss 210-meter-long located in the Structural Dynamics research Laboratory of NASA Langley is used in comprehensive active-vibration-control experiments on a realistic large space structure. Some predictions of the natural frequencies and mode shapes have been made based on the Finite Element model.

The purpose of this paper is to use the Truss-Beam model developed by Elias G. Abu-Saba to predict the natural frequencies of the Mini-Mast and then compare the results with those obtained from the FE model. Imperfections of the joints will be modeled, and joint contribution t the flexibility matrix of the structure will be noted. The natural frequencies will be obtained. An iterative procedure will be used to enhance the Truss-Beam model by comparing these results with experimental ones.

Neural Networks in Support of Manned Space

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Abstract

Many lobbyists in Washington have argued that artificial intelligence (AI) is an alternative to manned space activity. In actuality, this is the opposite of the truth, especially as regards artificial neural networks (ANNs), that form of AI which has the greatest hope of mimicking human abilities in learning, ability to interface with sensors and actuators, flexibility and balanced judgement.

This talk will begin by briefly reviewing ANNs and their relation to expert systems (the more traditional form of AI), and the limitations of both technologies. It will give a few highlights of recent work on ANNs, including an NSF-sponsored workshop on ANNs for control applications. It will then discuss current thinking on ANNs for use in certain key areas — the National Aerospace Plane, teleoperation, the control of large structures, fault diagnostics, and docking — which may be crucial to the long-term future of man in space.